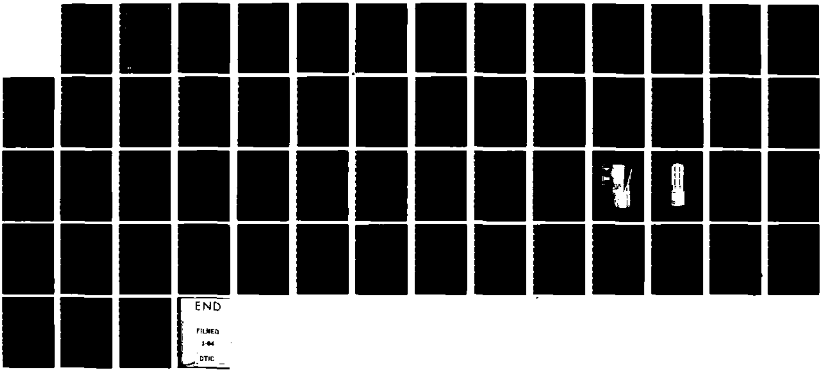
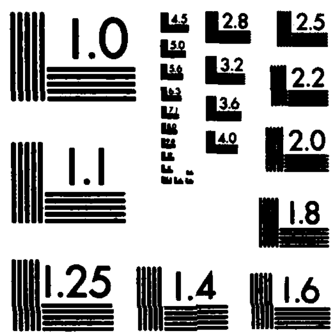
AD-A135 856 FLIGHT TESTS OF INSTRUMENTATION FOR AIRBORNE CARBON DIOXIDE FLUX MEASUREM..(U) NATIONAL AERONAUTICAL ESTABLISHMENT OTTAWA (ONTARIO) J I MACPHERSON OCT 83 1/1

UNCLASSIFIED NAE-AN-16 NRC-22751 F/G 4/1 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Canada

UNLIMITED
UNCLASSIFIED

AD-A135 856

FLIGHT TESTS OF INSTRUMENTATION FOR AIRBORNE CARBON DIOXIDE FLUX MEASUREMENT

by

J. I. MacPherson

National Aeronautical Establishment

AERONAUTICAL NOTE
OTTAWA
NAE-AN-16
OCTOBER 1983
NRC NO. 22751

National Research Council Canada
Conseil national de recherches Canada

NATIONAL AERONAUTICAL ESTABLISHMENT

SCIENTIFIC AND TECHNICAL PUBLICATIONS

AERONAUTICAL REPORTS:

Aeronautical Reports (LR): Scientific and technical information pertaining to aeronautics considered important, complete, and a lasting contribution to existing knowledge.

Mechanical Engineering Reports (MS): Scientific and technical information pertaining to investigations outside aeronautics considered important, complete, and a lasting contribution to existing knowledge.

AERONAUTICAL NOTES (AN): Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

LABORATORY TECHNICAL REPORTS (LTR): Information receiving limited distribution because of preliminary data, security classification, proprietary, or other reasons.

Details on the availability of these publications may be obtained from:

Publications Section,
National Research Council Canada,
National Aeronautical Establishment,
Bldg. M-16, Room 204,
Montreal Road,
Ottawa, Ontario
K1A 0R6

ÉTABLISSEMENT AÉRONAUTIQUE NATIONAL

PUBLICATIONS SCIENTIFIQUES ET TECHNIQUES

RAPPORTS D'AÉRONAUTIQUE

Rapports d'aéronautique (LR): Informations scientifiques et techniques touchant l'aéronautique jugées importantes, complètes et durables en termes de contribution aux connaissances actuelles.

Rapports de génie mécanique (MS). Informations scientifiques et techniques sur la recherche externe à l'aéronautique jugées importantes, complètes et durables en termes de contribution aux connaissances actuelles.

CAHIERS D'AÉRONAUTIQUE (AN): Informations de moindre portée mais importantes en termes d'accroissement des connaissances.

RAPPORTS TECHNIQUES DE LABORATOIRE (LTR): Informations peu disséminées pour des raisons d'usage secret, de droit de propriété ou autres ou parce qu'elles constituent des données préliminaires.

Les publications ci-dessus peuvent être obtenues à l'adresse suivante:

Section des publications
Conseil national de recherches Canada
Établissement aéronautique national
Im. M-16, pièce 204
Chemin de Montréal
Ottawa (Ontario)
K1A 0R6

UNLIMITED
UNCLASSIFIED

FLIGHT TESTS OF INSTRUMENTATION FOR AIRBORNE CARBON DIOXIDE FLUX MEASUREMENT

ESSAIS EN VOL DE L'APPAREILLAGE DE MESURE EN VOL DU FLUX DE DIOXYDE DE CARBONE

by/par

J.I. MacPherson

National Aeronautical Establishment

AERONAUTICAL NOTE
NAE-AN-16
NRC NO. 22751

OTTAWA
OCTOBER 1983

S.R.M. Sinclair, Head/Chef
Flight Research Laboratory/
Laboratoire de recherche en vol

G.M. Lindberg
Director/Directeur

SUMMARY

At the request of Agriculture Canada, the Flight Research Laboratory of the National Aeronautical Establishment (NAE) has operated the Twin Otter atmospheric research aircraft fitted with a CO_2 analyzer in order to assess the feasibility of making airborne carbon dioxide flux measurements. This report will summarize progress to date and present an analysis of the data collected during a series of nine test flights in August and September, 1982.

The experimental results show that it is possible to make realistic measurements of the heat and CO_2 fluxes from an aircraft instrumented to measure vertical gusts. Special tests and analysis procedures were conducted to investigate the accuracy of the carbon dioxide measurements. Recommendations for improvements in the design of future test programs are made.

RÉSUMÉ

À la demande d'Agriculture Canada, le Laboratoire de recherche en vol de l'Établissement aéronautique national (ÉAN) a évalué la faisabilité de mesurer en vol le flux de dioxyde de carbone à l'aide de l'avion de recherche atmosphérique Twin Otter, muni d'un doseur de CO_2. Le rapport résume les progrès réalisés jusqu'ici et présente une analyse des données obtenues au cours de neuf vols d'essais qui ont lieu en août et en septembre 1982.

Les résultats expérimentaux indiquent qu'il est possible de faire des mesures réalistes des flux de chaleur et de CO_2 à partir d'un avion muni d'instruments capables de mesurer les rafales verticales. On a utilisé des méthodes spéciales d'essai et d'analyse pour évaluer la précision des quantités de dioxyde de carbone mesurées. On fait des recommandations sur les améliorations à apporter lors de l'élaboration des programmes d'essai futurs.

CONTENTS

TABLES

ILLUSTRATIONS

1. INTRODUCTION

The increasing level of carbon dioxide (CO_2) in the atmosphere has led to much scientific speculation on long term effects as well as the formulation of analytical models to predict the consequences on global temperature, the weather, and the polar ice caps. Although reasonably accurate estimates can be made for the input of carbon dioxide to the atmosphere from the combustion of carbon-based fuels, much less well understood are the rates of exchange between the atmosphere and the oceans and vegetation.

For several years the Agrometeorology Section of Agriculture Canada has been developing instrumentation and conducting ground-based experiments to measure the CO_2 exchange rate between the atmosphere and various crops. In 1979 the Flight Research Laboratory of the National Aeronautical Establishment (NAE) was asked by Agriculture Canada (Ref. 1) to assess the feasibility of combining a CO_2 sensor with the gust measuring capability of an atmospheric research aircraft to make airborne measurements of the flux of carbon dioxide above various ecosystems. If successful, an aircraft offers the potential to quickly determine the CO_2 exchange rate over large areas for inputs to theoretical models, as well as to open the possibility of inferring the growth rates of crops and forests from these flux measurements.

In 1980 the NAE Twin Otter was used in a series of nine test flights, five with a CO_2 analyzer built for the Bedford Institute of Oceanography, and four with an open path analyzer developed by Agriculture Canada. Although the flights were restricted to the end of the growing season because of other aircraft commitments, valuable lessons were learned about the use of these sensors in airborne applications and suggestions were made for improvements (Reference 2 and 3). Resulting fluxes calculated by the eddy correlation technique were encouraging and further tests were planned.

In 1981 another series of 13 flights totalling 10 flying hours was flown using only the Agriculture Canada developed sensor. Several instrumentation problems were experienced which led to recommendations for additional improvements, but only limited further analysis of the flux data was attempted.

After undergoing aerodynamic and electronic refinements, the open path CO_2 analyzer was again installed in the Twin Otter for a ten hour series of test flights in August and September, 1982. The signal to noise ratio of the CO_2 analyzer was much improved. Consequently, in order to continue the assessment of the use of aircraft to make CO_2 flux measurements, the author has undertaken the analysis of 77 of the runs flown in this series of tests. The results are documented in this report and Reference 4, and foster suggestions for further instrumentation tests and an improved experimental design for the next test series. A major part of the Laboratory's continued interest in these tests stems from the fact that, in this particular test environment (very low altitude, low winds, and small vertical gusts damped by proximity to the surface), valuable experience is being gained on probing the limits of the capability of an aircraft to make accurate gust and flux measurements.

2. INSTRUMENTATION

The Twin Otter measures the three orthogonal components of atmospheric motion in aircraft- and earth-fixed axes utilizing a nose-mounted gust boom, a 3-axis Doppler radar, and a strapped-down inertial system consisting of accelerometers, and rate and attitude gyros. Atmospheric state parameters such as temperature and dew point are also measured, as are the aircraft motion, altitude (pressure and radio altimeter), and geographical position (GNS-500A). Three on-board microprocessors compute these parameters in real time and present one-second averages to the aircrew on a cockpit-mounted

plasma display unit. Data are processed by anti-aliasing low-pass filters with a 5 Hz cutoff, then digitized and recorded at a rate of 16 samples per second in serial-digital format on two tracks of a light-weight and reliable studio recorder. Table 1 lists the parameters recorded during these tests, track-1 for the raw sensor data and track-2 for computed time histories output from the microprocessors. A complete description of the aircraft, instrumentation, software, and playback data available is presented in Reference 5.

The Agriculture Canada open-path CO_2 analyzer, based on the differential absorption by CO_2 of infrared radiation at wavelengths of 4.3 and 4.7 μm, was mounted through the escape hatch in the cabin roof of the Twin Otter (Fig. 1). With the radiation source and detector just inside the cabin and the infrared beam reflected by a mirror 0.75 m above the fuselage, an in-air optical path length of 1.5 m was achieved. An output voltage proportional to carbon dioxide concentration was fed to the NAE signal conditioner where it was amplified, digitized and recorded on both tracks of the serial-digital recorder. Since a bias adjustment was made on the sensor after attaining flight speed and the test altitude, the recorded signal represented the fluctuations in the concentration of CO_2, with no attempt made to document the mean atmospheric concentration. After amplification, the calibration of the CO_2 output signal as recorded represented changes of 17.54 ppm per volt, giving a resolution of 0.343 ppm per bit and a full scale range of ±175 ppm.

The 1980 and 1981 tests showed that the output voltage from the CO_2 analyzer contained an unacceptable level of noise, the amplitude of which was proportional to airspeed (Ref. 2). This suggested that the noise was a result of the inconsistent reception by the detector of the reflected infrared beam, due to turbulence-generated vibration of the mirror and its support structure. Prior to the 1982 tests, the vertical tubes supporting the mirror and baffles were streamlined (Fig. 2), and noise levels appear to be significantly reduced.

Incident solar radiation was measured by a light sensor mounted vertically in the aft cabin roof. Its uncalibrated signal was recorded on both tracks of the NAE recorder and used primarily to document the passage of cloud shadows. Another device provided by Agriculture Canada to measure both incoming and reflected radiation was mounted on the cabin floor with its sensor looking vertically downward through an opening in the cabin floor and fuselage. It was used to obtain a relative measurement of the leaf area index of green vegetation. As its signal was internally recorded, it was not processed by NAE.

3.0 FLIGHTS

The aircraft was committed to another program through June and July, so flights had to take place late in the growing season between August 13 and September 10. Nine project flights, totalling just under ten flying hours, were conducted. Table 2 presents a brief summary of the dates and flights times, weather conditions, and the types of terrain and vegetation studied.

Data from the first three flights were unuseable because of instrumentation problems. On Flight 4 several runs were made over Corn Field C near Russell Airport, but near the end of the flight the CO_2 analyzer failed during the only investigation of soybean fields in the project. On August 26 the aircraft was operated from Kingston to make long runs over Lake Ontario to study the noise level and resolution of the CO_2 signal in an area of expected minimal fluctuations in carbon dioxide. This day was almost overcast and had the strongest winds of the experiment. On the return flight to Ottawa several long runs were made over mixed forest. On the first part of Flight 7 on August 31, two of the Agriculture Canada special test plots

near the Cedarview Road southwest of Ottawa were overflown. The first of these, Corn Field A, was the same field over which ground-based flux measurements were made prior to the flight tests, utilizing the same CO_2 analyzer carried aboard the aircraft. The second, Corn Field B, was centred about one kilometer northwest of A. Flight 7 concluded with a pair of long reciprocal passes over the Larose Forest and Mer Bleue, a marshy area, southeast of Ottawa.

The final two flights, although in September, had the clearest skies of the series and temperatures typical of the earlier flights. The winds were very light, especially on Flight 8. On September 8, five fairly long runs were performed over mixed farmland near Richmond, Ontario, followed by several passes over Corn Field A and Lac Deschênes. On September 10, eight runs each were made over Corn Fields A and B and a mixed forest just west of Field B.

Since the 1980 and 1981 studies showed that the CO_2 sensor had noise levels directly related to airspeed, the 1982 tests were flown at the lowest possible safe airspeed, utilizing about 15 degrees of flap. On most of the corn field, farmland, and forest runs, true airspeeds averaged about 50 m s^{-1} . For safety reasons the Lake Ontario series was conducted at higher airspeeds, around 60 m s^{-1} . Care was taken to minimize altitude excursions. Very low altitudes were achieved on some runs, averaging less than 8 m on the September 10 corn field runs, for example. Greater altitude variations were unavoidable over the Richmond farmland and the forests because of the presence of power lines and tall trees.

4.0 DATA ANALYSIS

Prior to the summer series of project flights, several improvements were made to the Twin Otter playback software. On a routine basis after each flight, the real-time computed data recorded

on track-2 are used to produce a flight path plot and a printout of winds, temperatures, positions etc. For the event-marker-in portions, which denote particular measurement runs, RMS and peak gust velocities are computed along with run averages of all pertinent parameters. For these tests the program was modified to include the run-average CO_2 vertical flux computed from the relationship:

$$\overline{\rho WCO_2} = \sum_{i=1}^{N} \frac{Wge(i)*CO_2(i)*\rho}{N} - \overline{Wge*}\ \overline{CO_2}\ *\rho$$

Where Wge is the vertical component of air velocity, CO_2 is the carbon dioxide concentration, and ρ is the density of air. The overbars represent run averages.

More detailed analysis of the flight data takes place on the NRC Time-Shared IBM 3033 System, where many programs and subroutines have been developed to utilize data recorded on track-1 of the Twin Otter recorder for the computations of gusts, fluxes, power spectra, etc. New software has now been added that uses the identical subroutines to produce the same outputs, but which employs the track-2 airplane-computed data as inputs.

For the 1982 test data, it was initially planned to perform all the analysis using only the track-2 parameters. It was discovered, however, that on many of the runs, the real-time computed wind components possessed biases at the start that took several seconds to decay. The resultant drifts are a product of the low filter breakpoint frequency ($0.02H_Z$) required in the real-time complementary digital filtering routine used to compute the aircraft inertial velocity components. The direct cause is the tight manoeuvring needed to

position the aircraft at low altitude over the usually small fields while avoiding obstacles at their margins. Any false drift in the vertical gust component clearly leads to inaccurate carbon dioxide and heat fluxes, especially for the short corn field runs where the drift often existed for up to a third of the recorded run. Consequently, it was decided to analyze all the runs using the raw track-1 data and to recompute the gusts and fluxes on the NRC Time-Shared System (TSS). Although the complementary filtering technique used in these programs is virtually identical to that in the aircraft real-time processing, drifts can be avoided by initiating the TSS analysis at the point where the aircraft has been stabilized over the test field.

The three components of the true gust velocity in airplane- and earth-fixed axes are computed by the methods detailed in Reference 5. For these data the earth axis system used has the Uge axis aligned north/south with a positive gust from the north. A positive lateral component, Vge, is from the east, and the positive sense for the vertical gust is upwards. Prior to the CO_2 flux calculation, the run average was removed from the vertical gust and CO_2 signals. The mounting location for the CO_2 analyzer was 6.5 m aft of the angle of attack sensor on the gust boom. In the CO_2 flux calculation, therefore, the Wge and CO_2 signals were time correlated by advancing the CO_2 signal by the integral number of data slices (usually 2) closest to 6.5*16/(true airspeed).

Run-average heat and CO_2 fluxes were calculated by two procedures. Method A was to simply average the product over the entire event-in portion of the run, i.e.

$$\overline{\rho W CO_2} = \sum_{i=1}^{N} \frac{(Wge\ (i)-\overline{Wge}) * (CO_2\ (i)-\overline{CO_2}) * \rho}{N}$$

In Method B, the co-spectrum of the product was integrated over a selected wavelength range from 10 to 800 m. Since the project runs varied in length from about one to greater than 13 km, a meaningful comparison of fluxes between runs over different terrains can really only be achieved by using a common limited wavelength band. It is important to note that all of the RMS values and heat fluxes presented in this report were computed by Method B. To show the above-mentioned variations, three computations of the carbon dioxide flux are given for each run, i.e. track-2 and Methods A and B for track-1 (Tables 3-7). For the final summaries (Tables 8-10), only fluxes calculated over the 10 to 800 m wavelength range are included. No attempt was made to correct the CO_2 fluxes for the effects of the sensible and latent heat fluxes, so the resultant CO_2 fluxes could be overestimated by up to twenty per cent over land and possibly more over water (Ref. 6).

A total of 77 runs was analyzed. Outputs included printed listings of winds, temperatures, flight conditions, RMS gust velocities, flux estimates, spectra, and co-spectra. Time histories of the following 10 parameters were written to disk and backed-up to magnetic tape for storage: event marker, 3-axis gust components, radiometer, radio altimeter height, temperature, CO_2 signal, CO_2 flux, and the cumulative average of the CO_2 flux. The last parameter was computed from the relationship:

$$\text{SUMF}(i) = \frac{\sum_{j=1}^{i} \text{Flux}(j)}{i} \quad \text{Where Flux}(j) = (\text{Wge}(j) - \overline{\text{Wge}}) * (\text{CO}_2(j) - \overline{\text{CO}_2}) * \rho$$

Time history plots of the important parameters were prepared for all the runs, examples of which are shown in Figures 3 to 8 for the various terrains studied. It must be noted that the radio altimeter

height shown (RALT) is measured from the bottom of the fuselage to the surface. Since the CO_2 sensor is mounted on the top of the fuselage, the actual carbon dioxide sample was taken 2.3 m above the height shown in the figures and tables below. Data from only 70 of the 77 runs are presented in this report. There were occasional false spikes in the vertical gust and CO_2 signals, such as seen in Figure 8. Examination of the flux and SUMF time histories showed that on most runs these made no significant contribution to the flux, but where the opposite was true, the run was excluded from further analysis.

Gust, CO_2 , and temperature spectra, and the Wge*CO_2 and heat co-spectra were output to a labelled dataset for each run. A special program was then used to produce average unnormalized spectra and co-spectra for a particular series of runs, e.g. for a particular terrain type (Figures 9 to 18).

Copies of the time histories on magnetic tape, analog plots, and the summary tables have been forwarded to Macdonald College of McGill University for their analysis under contract to Agriculture Canada.

5.0 DISCUSSION OF RESULTS

Tables 3 to 7 present the computed results for each run, grouped by terrain type and flight. After each series of runs on a given flight, the average values for all runs are given along with the standard deviation, σ , to show the variation between runs. These averages and standard deviations are carried to the summary Table 8 to facilitate comparison of results.

Perhaps the most noticeable observation from Tables 3 to 7 is the large run-to-run variation in the measured CO_2 flux for all three methods of computation. In most cases the track-2 CO_2 fluxes display greater variability than the track-1 results, principally due to the drifts in the track-2 vertical wind component on some runs as discussed in Section 4.0. As would be expected, the average track-1B fluxes are generally smaller than those computed from track-1 data using Method A, since the contributions by eddies with wavelengths longer than 800 m are excluded. The heat flux data appear to be less variable than the CO_2 fluxes. The RMS of the vertical gust velocity and the CO_2 concentration tend to be fairly consistent from run to run. Throughout all the tests, the standard deviation of the RMS vertical gust velocity averages only about 0.1 m s^{-1}, suggesting that the considerable variability in the fluxes is not related to the vertical gust component.

Despite the variability of the fluxes between runs, the results of this feasibility study should be considered encouraging. The average heat and carbon dioxide fluxes appearing in Table 8 are of the correct sign and of reasonable magnitude, comparing favourably with previous ground-based measurements. In the latter case it has been an accepted practice to average the results of several runs, as has been done here. This appears to be especially necessary when only short runs can be made, as was the case for the corn fields.

The analysis of flux data has usually been based on the assumption of steady state, i.e. a time invariant boundary layer in equilibrium with the sources and sinks of CO_2 and heat. This is unlikely to have been the case for these tests, for wind shifts, moving cloud shadows, etc. can cause singular events leading to the over or underestimation of the turbulent fluxes. For small fields with

marginal fetch, wind shifts can bring air from adjacent fields with different vegetation and presumably different CO_2 concentrations. Although there are only a limited number of long runs in the 1982 study (Larose, Richmond, and Lake Ontario), these data and those of Reference 3 support the observation of improved consistency with the length of the flight path. Examination of the traces of the cumulative average CO_2 flux (SUMF) for the longer runs reveals that at least 30 seconds, and often a minute (3 km), is required for them to reach a stable level representative of their final value.

Run 04-08C is a good example of a singular event discussed above, one with the largest track-1B CO_2 flux and second largest heat flux of the entire experiment (Table 4, Fig. 4). In the 26-30 second range of the time histories, there is a 200 m wide updraft averaging about 2 m s^{-1}, well correlated with an increase in temperature and a decrease in CO_2 concentration. None of the other runs over Corn Field C that day showed such an event, nor can anything unique be found in the conditions for this particular run. It should be noted, however, that the average CO_2 flux for all the passes over this field (-46 kg ha^{-1} h^{-1}, Table 8) is the largest recorded in these tests. This is the earliest flight of those reported here (August 23) and would be expected to exhibit the largest CO_2 exchange rates. Also the winds averaged 209 degrees at 6.7 m s^{-1}, the strongest for all the corn field runs, and probably contributed to the increased flux levels.

Figures 9 to 17 depict average co-spectra for the heat and CO_2 fluxes for the various types of terrain studied. The standard deviation of the spectral estimates at each frequency is relatively large since the variability of the fluxes themselves is considerable. Nevertheless, these presentations are useful for showing the size of the eddies contributing to the fluxes and for examining the potential differences between vegetation types.

At wavelengths shorter than about 30 m, there is a negligible contribution to the CO_2 flux, but a small but significant contribution to the heat flux. This is an indication that, for an airspeed of 50 m s^{-1}, the upper limit of the frequency response of the CO_2 analyzer is about 1 to 1-1/2 Hz in the airborne application. This is lower than its reported performance in ground-based studies, and suggests the need for additional tests of this aspect of its operation.

For most of the plots the heat and CO_2 co-spectra show a similar dependence on wave number, but are opposite in sign. This indicates that basically the same eddies are responsible for the vertical transfer of heat and carbon dioxide, and that during the photosynthetically active part of the day, the vegetation is a source of heat and a sink for CO_2.

The co-spectra show that the bulk of the CO_2 and heat transfer is carried by eddies with wavelengths in the 50 to 500 m range. There are observable differences in the locations of the peaks for different days and terrains, which tend to be more evident in the heat co-spectra because they are less variable. A comparison of Figures 9 and 11, for example, shows heat and CO_2 transfer at longer wavelengths over Field C than Field A. If this trend is real, it could be due to the higher altitude flown over C, the stronger winds, or perhaps the greater photosynthetic activity earlier in the season. Similarly the runs over the Larose Forest illustrate an increased contribution to the heat flux by long wave length eddies up to 800 m (Fig. 13). Examination of the vertical temperature profiles recorded by the aircraft to a height of 300 m shows the greatest gradients on the day Corn Field C was studied, while the Larose runs were flown on the day with the second steepest lapse rate. Reference 7 indicates that a shift to longer wavelengths in the co-spectra can be expected with increased atmospheric instability.

Confidence in the results and in the use of the eddy correlation technique to compute the fluxes is bolstered somewhat by the co-spectra averaged for the 10 runs over water (Fig. 12). As would be anticipated, the co-spectral estimates and mean fluxes over water are an order of magnitude lower than those for the runs over vegetation. There is no noticeable preference for contributions at any particular wavelength, indicating an absence of correlated error between the vertical gust component and the CO_2 or temperature signals.

Tables 9 and 10 present the final summary of the average carbon dioxide and heat fluxes versus flight number and terrain type. It is difficult to draw firm conclusions from these data. There are an insufficient number of entries in each category to positively relate observed variations to physical explanations. Trends suggested by the data in one category are sometimes contradicted by the limited results from another category. Obviously there are many factors that can affect the heat and carbon dioxide fluxes. These include the altitude flown, the incident radiation, wind speed and direction, the temperature and moisture content of the soil, plant stress, atmospheric stability, and the phase of the growing season. As this program was basically an instrument test and feasibility study, not all of these factors were documented to the degree required for meaningful correlation with the average fluxes. It is planned to do so in the next test program. It is also recommended that, in the next CO_2 flux measuring program, the test areas be restricted to a number that can be investigated on <u>every</u> flight. With entries at all possible array locations in summary tables such as 9 and 10, significant trends in the data may then become apparent.

6.0 SPECIAL TESTS

An important aspect of this feasibility study was the investigation of possible contributors to the run to run flux variations. At this point the subject of the reliability and accuracy of the CO_2 analyzer should be addressed in more detail. Particular questions to be considered are whether the streamlining of the mirror supports has completely eliminated noise problems, and whether the excursions in the CO_2 analyzer output represent actual CO_2 fluctuations or are partially a result of some other interference effect.

Special tests were performed to attempt to answer these questions. These included low altitude runs over water distant from shore where real CO_2 fluctuations would be expected to be a minimum. The results in Table 5 are promising, for they show the anticipated very low heat and CO_2 fluxes with small standard deviations, especially when compared with the over-land runs (Table 8). However, the eddy correlation technique used to compute the fluxes can mask noise problems. This is one of its advantages under normal circumstances. A signal contaminated with random noise can be multiplied by another to give a good average flux estimate, as long as the noise on the one signal is uncorrelated with the second signal. The flight results therefore indicate that the measured CO_2 concentration fluctuations are either real or, if they have a false component, it is uncorrelated with the vertical gust velocity, so realistic flux estimates still result.

6.1 Frequency Response of the CO_2 Analyzer

Examination of Figures 3 and 4 reveals that the CO_2 trace has less high frequency content than the gust and temperature time histories. To further investigate this point, average power spectra for the vertical gust, temperature, and CO_2 signals were computed for 23

runs over Corn Field A (Figure 18). The Wge and temperature spectra show the expected -5/3 slope at high frequencies; the CO_2 spectra for the corn field runs and all forest runs do not. The steep slope at $k > 0.02 m^{-1}$ indicates a reduced response at frequencies greater than about 1 Hz. If turbulence generated by the flow about the mirror supports and baffles caused mirror vibration and resultant noise in the CO_2 output signal, it would be expected to appear at these frequencies. The lack of high frequency fluctuations could be an indication that the streamlining of the mirror supports has had the desired effect of improving the signal to noise ratio. The steep slope of the CO_2 spectrum is of concern, however, and deserves additional investigation in future tests.

6.2 CO_2 Fluctuations and Sideslip Angle

The average RMS value for the CO_2 concentration is given in Table 8 for each series of runs. Over land the values are from 3 to 4 ppm. Over water they are 2.3 to 2.4 ppm, higher than expected and perhaps an indicator of a level of error. Close examination of the CO_2 traces shows that many of the signal fluctuations occur at frequencies near the short period and lateral oscillatory modes of the aircraft (0.3 to 0.5 Hz). Streamlining the mirror supports might have made the analyzer sensitive to lateral forces caused by sideslip. If this were the case, the CO_2 signal would be expected to increase with either positive or negative sideslip.

The analysis software was modified to compute sideslip angle β at the mounting location of the CO_2 analyzer. The correlations between the CO_2 signal and β the lateral gust velocity were also computed. Three runs were analyzed with this modified software, Run05-11L over Lake Ontario, Run 07-01F over the Larose Forest, and Run 09-CI, a special test in which the aircraft was flown in relatively

smooth air at 1200 ft above ground and subjected to pitch, roll, and yaw control inputs. Figure 19 shows the time histories for the three runs. The top two traces represent the lateral and vertical gust velocities computed in earth axes with the x axis aligned with the run-averaged heading of the aircraft. The Vge trace approximates the lateral gust velocity experienced by the CO_2 sensor. The third and fourth traces depict the sideslip angle β at the sensor and the CO_2 signal respectively. It can be seen that substantial sideslip angles are generated, up to about 7 deg. at 'A' in the forest run and after 'B' during the yawing manoeuvres in the control input tests. Although at some points there is the suggestion of a relationship between the sideslip angle and the CO_2 signal, there does not appear to be a conclusive one to one correspondence between β excursions and positive CO_2 fluctuations. Also, in the control input case, there is no noticeable increase in CO_2 activity after 'B' when the yawing manoeuvres commence.

The bottom three traces in Figure 19 show the products of CO_2 times β, lateral gust velocity, and vertical gust velocity respectively. The lateral flux of CO_2 tends to show larger excursions than the vertical flux for the forest and lake runs, but about the same for the control input case. This is not unexpected, for at the low altitudes flown in the first two cases, the vertical gusts are damped because of proximity to the surface. Moreover, since each run had a considerable crosswind component, the lateral flux of CO_2 should equal or exceed the vertical transport.

Since it was postulated that CO_2 fluctuations could be correlated with sideslip at particular frequencies, power spectra for β and CO_2 have been computed for the three special test runs. The spectra at the bottom of Figure 20 show peaks clearly associated with the yawing oscillations of the aircraft at wave numbers ranging from 3.5 to 6.8 x 10^{-3} m^{-1} (frequencies of 0.19 to 0.32 Hz). This is especially evident for the forced yaws in the control input case, where

the peak in the spectrum is more than an order of magnitude higher than it would have been without the rudder inputs. If side forces cause mirror deflections that shift the reflected infrared beam partially off the detector, then a false positive CO_2 reading would result for both left and right sideslips, i.e. the CO_2 spectrum would show a peak at twice the frequency of the β oscillations. The CO_2 spectra in the upper part of Figure 20 show no obvious peaks at frequencies corresponding with either the β spectral peak or twice its wave number. It can be concluded that very little, if any, of the CO_2 signal fluctuation is caused by deflection of the mirror support structure due to aerodynamic side forces.

6.3 Effects of Aircraft Wake and Exhaust During Repeated Runs

For the smaller fields, runs on reciprocal headings have been made at intervals as short as 1-1/2 minutes, bringing into consideration the possible contamination of the data as a result of the previous pass of the aircraft. In light wind conditions, or for runs nearly along the wind direction, it is possible that the atmosphere disturbed by the aircraft wake will not be returned to a natural equilibrium prior to the next passage of the aircraft. Resultant disturbances would be difficult to detect and impossible to correct in the data.

A more serious potential problem with repeat passes is contamination of the CO_2 readings by carbon dioxide emitted in the engine exhaust from previous runs. An example calculation will illustrate this. Assume that in the 1-1/2 minutes between passes, the exhaust released in one second is uniformly mixed in a volume of air defined by 3 times the aircraft wingspan (3 x 20 m), the run altitude (12 m), and the distance flown in one second (50 m). At the power setting required for 100-knot cruise near sea level, each PT6 engine burns at least 230 lb per hour of fuel to produce 450 lb of CO_2 (Ref.

8). In one second, then, $\frac{2 * 450 * 454}{3600} = 113$ grams of CO_2 are produced

and the resulting concentration is:

$$\frac{113}{50*12*60} \frac{\text{g } CO_2}{m^3} * \frac{1}{100^3} \frac{m^3}{cm^3} * \frac{1}{1.2*10^{-3}} \frac{cm^3}{\text{g air}} = 2.6*10^{-6} \frac{\text{g } CO_2}{\text{g air}}$$

$$= 2.6*10^{-6} * \frac{29}{44} = 1.7*10^{-6} \text{ parts } CO_2 \text{ per part air}$$

This 1.7 ppm concentration is of the same order as the measured RMS of the CO_2 signal. Even relaxing the above assumptions to allow a greater dissipation of the wake between runs will not eliminate the potential for contamination of the CO_2 measurements by the exhaust, for there may be isolated pockets of higher exhaust concentration caused by some environmental condition or the wingtip trailing vortices. For the data in this report, the problem could likely only occur during the corn field runs. Fortunately, in most cases there was a cross-track wind component, which even in the worst case, would have transported the aircraft wake 240 m laterally between runs. For Runs 3A, 5A, and 7A of Flight 9, a diagonal pass across the field was made just 80 seconds after a north-south run. Although the aircraft wake was probably crossed on these runs, there are no apparent anomolies in the temperature, gust, or CO_2 concentration data that can be conclusively associated with interception of the wake or exhaust. Nevertheless, since the possibility of data contamination does exist, it is highly recommended that in future CO_2 flux measurements, longer fields should be chosen and repeated passes avoided. If this is impracticable, all runs should be flown crosswind with perhaps at least 3 minutes between passes.

7.0 CONCLUSIONS

The feasibility of measuring carbon dioxide fluxes from an aircraft has been demonstrated. Carbon dioxide and heat fluxes averaged for several runs were of the correct sign and had magnitudes consistent with previous ground-based measurements.

The aerodynamic improvements made to the Agriculture Canada open path CO_2 analyzer appear to have improved its signal to noise ratio by eliminating high-frequency, airspeed-dependent fluctuations associated with vibration of the mirror support structure. Further flight testing of the analyzer is required to determine why its response at frequencies above 1 Hz appears limited in the airborne application compared with its ground-based performance.

The output signal from the CO_2 sensor possessed fluctuations that were suspected of being too large, particularly in over-water tests. Special analysis procedures demonstrated that these excursions were not correlated with sideslip angle, and were therefore not a result of lateral aerodynamic forces on the mirror support structure. No other correlations were found that suggested these CO_2 readings were anything but real. Nevertheless, it is felt that a CO_2 analyzer should be developed that is mounted entirely within the aircraft fuselage and samples air ducted to it from an external inlet.

The computed heat and CO_2 fluxes showed considerable variation from run to run. Even when averaged over all runs for a particular flight and vegetation type, it was difficult to relate the resultant fluxes to environmental conditions, terrain, etc. To that end, considerable attention must be given to the design of future experiments in order to make such conclusions possible. The next test series should cover a larger part of the growing season to provide greater variations in photosynthetic activity (eg, mid-June to the end of August). The number of test areas (terrains) should be restricted to about four, with <u>each</u> flown on <u>every</u> flight. One of these could be adjacent to the NAE Mobile Meteorological Tower, which would provide useful supporting wind and temperature data at four levels in the lower 30 m of the atmosphere. Run lengths must be at least three

kilometers, and repeated passes, if done at all, must be arranged so as to avoid contamination by the turbulent wake and exhaust of the previous pass. For every flight a sounding to about 5000 ft should be flown to document the stability of the atmosphere. Then, given a sufficient number of test cases, average fluxes appearing in tables such as 9 to 10 in this report, can be examined for trends that can be related known physical processes and environmental conditions.

8.0 REFERENCES

1. Letter to Mr. A.D. Wood, former Head, Flight Research Laboratory from R. Desjardins, Agrometeorology Section, Agriculture Canada, dated Sept. 10, 1979.

2. MacPherson, J.I. — Flight Experiments to Measure the Flux of Carbon Dioxide Above Various Ecosystems. NRC, NAE Laboratory Technical Report LTR-FR-74, Ottawa, October 1980.

3. Desjardins, R.L., Brach, E.J., Alvo, P., Schuepp, P.H. — Aircraft Monitoring of Surface Carbon Dioxide Exchange. Science Volume 216, No. 4547, May 1982.

4. Desjardins, R.L., MacPherson, J.I., Alvo, P., Schuepp, P.H. — Ground Referencing and Update on Flight Program for Airborne CO_2 Measurement. Paper Presented at the Sixteenth Conference on Agriculture and Forest Meteorology. Fort Collins, Colorado, April 1983.

5. MacPherson, J.I., Morgan, J.M., Lum, K. — The NAE Twin Otter Atmospheric Research Aircraft. NRC, NAE Laboratory Technical Report LTR-FR-80, Ottawa, March 1981.

6. Webb, E.K., Pearman, G.I., Leuning, R. — Correction of Flux Measurements for Density Effects Due to Heat and Water Vapour Transfer. Quarterly Journal of the Royal Meteorological Society, Vol. 106, pp. 85-100, 1980.

7. McBean, G. — Instrument Requirements for Eddy Correlation Methods. Journal of Applied Meteorology, Vol. 11, pp. 1078-84, 1972.

8. Personal Communication with J.W. Bird, Engine Laboratory, NRC Division of Mechanical Engineering, and P. Sampath, Combustion Department, Pratt and Whitney, Mississauga.

TABLE 1

DATA RECORDED ON CF-POK — AGRICULTURAL PROJECT — 1982

Channel	Track 1	Track 2
0	GMT	GMT
1	9-Level Event Marker	9-Level Event Marker
2	Doppler Vx	GMT - hour
3	Doppler Vy	GMT - minute
4	Doppler Vz	GMT - second
5	Dynamic Pressure (Airspeed)	Latitude - degrees
6	Magnetic Heading	Latitude - minutes
7	Radio Altimeter Height	Longitude - degrees
8	Total Temperature	Longitude - minutes
9	Dew Point	Range from Reference
10	GNS Latitute	Bearing from Reference
11	GNS Longitude	True Heading
12	Vertical Acceleration	Wind Speed
13	Lateral Acceleration	Wind Direction
14	Longitudinal Acceleration	Static Pressure (corrected)
15	Wind Direction	True Airspeed
16	Wind Speed	Pitch Attitude
17	Total Temperature (fine)	Roll Attitude
18	Angle of Attack	Uge - North/South Wind Component
19	Angle of Sideslip	Vge - East/West Wind Component
20	Pitch Attitude	Wge - Vertical Wind Component
21	Roll Attitude	* Vertical Wind by Pressure Method
22	Pitch Rate	Static Temperature
23	Yaw Rate	Reverse Flow Temperature
24	Roll Rate	Dew Point
25	—	* Rate of Change of Pressure Height
26	CO_2 Analyzer	* Waire
27	Radiometer	Radio Altimeter Height
28	Static Pressure	* PS25
29	True Airspeed	CO_2 Analyzer
30	Time - Seconds	Radiometer

* Computed parameters recorded for special software tests done on same flights.

TABLE 2

FLIGHT SUMMARY — CO_2 FLUX MEASUREMENT, 1982

Flt	Date 1982	Times – GMT Takeoff	Landing	Hours	Weather	Temp[(1)] °C	Winds True - m S^{-1}	Test Areas	Instrumentation
1	Aug. 13	1853	1946	0.9	Cloudy, TCu	–	–	Test over water, corn, and forest	No data – slave CPU down
2	Aug. 16	1854	1924	0.5	Partially cloudy, 6/10 TCu	–	NW	Lac Deschênes	No data – tape reversed
3	Aug. 18	1520	1630	1.2	Sunny, 2/10 Cu	19	WSW 4	Lac Deschênes, Larose Forest Corn Field C	Data spikes; doppler memory over water
4	Aug. 23	1831	1926	1.0	7/10 Cumulus	22	SSW 7	Corn Field C, Soybean Field	CO_2 sensor u/s after 1912 Z
5	Aug. 26	1517	1703	1.8	7/10 Cumulus Alto Cumulus	17	SW 8	Lake Ontario	
6	Aug. 26	1858	1939	0.7	9/10 Str. Cu Showers	21	SW 5	Forest, Fields, and Corn on Kingston-Ottawa Leg	
7	Aug. 31	1522	1630	1.2	Strato Cu 3/10 Alto Cu 1/10	17	NW 5	Corn Fields A and B, Larose Forest, Mer Bleue	Track 2 channel order changed, data OK
8	Sep. 08	1810	1925	1.3	Sunny, 1/10 Cu	16	Almost calm	Fields near Richmond, Corn Field A, Lac Deschênes	Some CO_2 and α spikes
9	Sep. 10	1529	1602	0.6	Sunny	22	SW 4	Corn Fields A and B and Forest near Field B	

(1) At Ottawa Airport at takeoff.

TABLE 3

FLUX SUMMARY — CORN FIELD A

Flt	Run	Alt m	Dist km	$\sigma_{W_{ge}}$ m S^{-1}	σ_{CO_2} ppm	Heat Flux Watts m^{-2}	CO_2 Flux kg ha^{-1} h^{-1} Trk 2	Trk 1A	Trk 1B
7	1A	17	1.63	0.62	4.0	81	-12	-11	-7
	2A	18	1.64	0.53	3.7	61	57	-11	-22
	3A	18	1.80	0.71	3.9	36	12	-2	-6
	4A	15	1.66	0.76	4.2	61	-2	5	6
	5A	13	1.01	0.53	3.2	54	-15	-8	-2
AVG		16	1.55	0.63	3.8	59	8	-6	-6
σ				0.09	0.3	14	29	6	9
8	1A	27	1.54	0.66	3.7	72	-53	-35	-35
	2A	25	1.62	0.81	3.7	129	-57	-58	-74
	3A	26	2.03	0.63	3.5	88	-5	-17	5
	4A	27	1.97	0.76	3.3	76	-32	-34	-18
	6A	25	1.97	0.87	2.8	93	-7	-17	-11
	7A	24	2.22	0.61	3.2	73	11	-14	-24
	8A	25	2.25	0.87	2.6	109	-19	-20	-23
	9A	27	2.13	0.58	3.5	65	-35	-43	-38
	10A	26	2.16	0.67	3.3	67	-19	-19	-7
	11A	25	2.17	0.52	3.2	66	-12	-12	-21
AVG		26	2.01	0.70	3.3	84	-23	-27	-25
σ				0.12	0.3	20	20	14	20
9	1A	8	2.06	0.58	4.6	113	-149	-89	-50
	2A	9	1.10	0.61	3.9	86	46	9	-11
	3A	8	1.69	0.51	4.6	99	-75	-50	-44
	4A	8	1.05	0.66	3.7	119	24	-15	-31
	5A	8	1.74	0.57	3.7	91	-47	-32	-12
	6A	7	1.20	0.60	5.6	102	5	-38	-43
	7A	7	1.59	0.50	4.0	78	-59	-59	-7
	8A	7	1.18	0.50	4.6	67	0	5	3
AVG		8	1.45	0.57	4.3	94	-32	-34	-24
σ				0.05	0.6	17	59	31	19

TABLE 4

FLUX SUMMARY — CORN FIELDS B AND C

Flt	Run	Alt m	Dist km	$\sigma_{W_{ge}}$ m S^{-1}	σ_{CO_2} ppm	Heat Flux Watts m^{-2}	CO_2 Flux kg ha^{-1} h^{-1} Trk 2	Trk 1A	Trk 1B
FIELD B									
7	1B	15	1.61	0.66	3.0	141	-27	-37	-29
	2B	16	1.79	0.55	3.9	80	-1	-10	-9
	3B	17	1.82	0.82	4.0	185	-28	-31	-23
	4B	14	1.86	0.50	4.0	16	30	-8	1
AVG		16	1.77	0.63	3.8	106	-7	-22	-15
σ				0.12	0.4	64	24	13	12
9	1B	9	1.30	0.80	5.3	100	-3	-16	-6
	3B	7	1.56	0.66	4.0	95	14	7	4
	4B	7	1.37	0.55	3.5	22	-6	-15	-7
	5B	8	1.70	0.62	3.9	116	-5	-44	-47
	6B	7	1.62	0.49	4.2	59	-15	-11	-12
	7B	7	1.49	0.47	3.9	42	14	8	6
	8B	7	1.46	0.54	4.2	53	-15	-20	-11
AVG		7	1.50	0.59	4.1	70	-2	-13	-10
σ				0.11	0.5	32	11	16	16
FIELD C									
4	1C	42	1.64	0.63	3.0	42	-57	-29	-32
	3C	21	1.55	0.62	5.3	20	-7	-16	-35
	4C	40	1.98	0.85	4.2	76	-66	-65	-72
	5C	29	1.60	0.62	3.3	34	-26	-23	-25
	6C	28	1.95	1.00	2.2	112	-30	-46	-43
	7C	39	1.63	0.82	3.3	88	-23	-62	-66
	8C	20	1.97	0.97	3.5	210	-61	-76	-98
	9C	20	1.56	0.68	3.3	22	20	8	7
AVG		30	1.74	0.77	3.5	76	-31	-39	-46
σ				0.15	0.9	60	28	27	31

TABLE 5

FLUX SUMMARY — LAKES

Flt	Run	Alt m	Dist km	σ_{Wge} m S^{-1}	σ_{CO_2} ppm	Heat Flux Watts m^{-2}	CO_2 FLUX kg ha^{-1} h^{-1} Trk 2	Trk 1A	Trk 1B
LAKE ONTARIO									
5	4L	23	7.53	0.58	2.6	4	18	-2	-2
	5L	22	9.99	0.31	2.3	1	-8	1	0
	6L	33	6.84	0.37	2.1	1	1	0	3
	7L	34	13.33	0.34	2.3	0	-6	-8	-5
	8L	44	7.94	0.42	2.8	5	-3	-3	0
	11L	23	11.93	0.36	2.1	2	0	3	1
	12L	38	8.20	0.62	2.8	-6	-17	-5	-5
AVG		31	9.39	0.43	2.4	1	-2	-2	-1
σ				0.11	0.3	3	10	3	3
LAC DESCHÊNES									
8	1L	27	2.99	0.48	2.1	1	-11	2	-3
	3L	29	0.89	0.26	2.6	-2	-7	1	1
	4L	27	1.93	0.38	2.3	0	6	6	7
AVG		28	1.93	0.37	2.3	0	-4	3	2
σ				0.09	0.2	1	7	2	4

TABLE 6

FLUX SUMMARY — FOREST

Flt	Run	Alt m	Dist km	σ_{Wge} m S^{-1}	σ_{CO_2} ppm	Heat Flux Watts m^{-2}	CO_2 Flux kg ha^{-1} h^{-1} Trk 2	Trk 1A	Trk 1B
KINGSTON TO OTTAWA									
6	1F	42	10.79	0.86	4.4	-6	-31	3	-1
	2F	36	14.09	0.83	3.9	20	-8	0	-5
	3F	34	6.88	0.87	3.5	-9	24	7	-1
AVG		37	10.58	0.85	4.0	2	-5	3	-2
σ				0.02	0.4	13	23	3	2
LAROSE FOREST									
7	1F	28	11.88	0.74	3.3	122	-28	-37	-21
	2F	32	12.44	0.90	3.3	160	-23	-37	-34
AVG		30	12.16	0.82	3.3	141	-26	-37	-28
σ				0.08	0.0	19	3	0	6
NEAR FIELD B									
9	1F	23	1.21	0.95	4.4	126	-47	-52	-42
	2F	28	1.83	0.85	2.8	94	50	18	11
	3F	25	1.19	0.83	3.3	135	-65	-71	-58
	4F	18	0.71	0.65	3.7	53	14	14	7
	5F	19	1.56	1.00	3.7	260	-5	-43	-45
	7F	18	1.82	0.93	4.0	157	-19	0	-2
	8F	23	1.37	0.92	4.0	106	34	67	68
AVG		22	1.38	0.88	3.7	134	-5	-10	-9
σ				0.11	0.5	60	39	45	40

TABLE 7

FLUX SUMMARY — RICHMOND FARMLAND, MER BLEUE

Flt	Run	Alt m	Dist km	$\sigma_{W_{ge}}$ m S^{-1}	σ_{CO_2} ppm	Heat Flux Watts m^{-2}	CO_2 Flux kg ha^{-1} h^{-1} Trk 2	Trk 1A	Trk 1B
RICHMOND FARMLAND									
8	1R	29	5.55	0.64	3.0	61	-28	-24	-25
	2R	26	5.65	0.82	3.3	85	-70	-42	-32
	3R	29	3.29	0.76	3.2	82	-21	-19	-18
	4R	26	3.06	0.62	3.5	61	-9	-23	-5
	5R	32	6.29	0.62	3.2	78	-36	-40	-17
AVG		28	4.77	0.69	3.2	73	-33	-30	-19
σ				0.08	0.2	10	21	9	9
MER BLEUE									
7	2M	18	5.94	0.61	3.0	95	-10	-12	-11

TABLE 8

DATA AVERAGES BY FLIGHT AND TERRAIN

	Flt	Date 1982	Runs	Dist km	Alt m	Temp(1) °C	Winds °T/m S^{-1}	Vertical Gust(2) AVG RMS - (σ) m S^{-1}	CO_2(2) AVG RMS - (σ) ppm	Heat Flux(2) AVG - (σ) Watts m^{-2}	CO_2 Flux(2) AVG - (σ) Kg ha^{-1} h^{-1}
CORN FIELD A	7	AUG 31	5	1.55	16	16.5	318/5.3	0.63 (0.09)	3.8 (0.3)	59 (14)	-6 (9)
	8	SEP 8	10	2.01	26	16.8	220/2.3	0.70 (0.12)	3.3 (0.3)	84 (20)	-25 (20)
	9	SEP 10	8	1.45	8	22.9	235/4.5	0.57 (0.05)	4.3 (0.6)	94 (17)	-24 (19)
CORN FIELD B	7	AUG 31	4	1.77	16	16.5	327/4.8	0.63 (0.12)	3.8 (0.4)	106 (64)	-15 (12)
	9	SEP 10	7	1.50	7	23.1	219/3.9	0.59 (0.11)	4.1 (0.5)	70 (32)	-10 (16)
CORN FIELD C	4	AUG 23	8	1.74	30	20.4	209/6.7	0.77 (0.15)	3.5 (0.9)	76 (60)	-46 (31)
LAKES											
– ONTARIO	5	AUG 26	7	9.39	31	18.3	227/8.8	0.43 (0.11)	2.4 (0.3)	1 (3)	-1 (3)
– DESCHÊNES	8	SEP 8	3	1.93	28	16.6	VAR/2.9	0.37 (0.09)	2.3 (0.2)	0 (1)	2 (4)
FOREST											
– KING-OTT	6	AUG 26	3	10.58	37	21.5	232/4.7	0.85 (0.02)	4.0 (0.4)	2 (13)	-2 (2)
– LAROSE	7	AUG 31	2	12.16	30	17.0	326/3.5	0.82 (0.08)	3.3 (0.0)	141 (19)	-28 (6)
– NEAR B	9	SEP 10	7	1.38	22	22.8	237/2.9	0.88 (0.11)	3.7 (0.5)	134 (60)	-9 (40)
RICHMOND FARMS	8	SEP 8	5	4.77	28	16.5	VAR/1.3	0.69 (0.08)	3.2 (0.2)	73 (10)	-19 (9)
MER BLEUE	7	AUG 31	1	5.94	18	16.9	340/3.4	0.61	3.0	95	-11

(1) At flight level
(2) Data in last 4 columns from Tables 3 to 7, computed from spectra and cospectra 10 - 800 m band.

TABLE 9

CO_2 FLUXES

Flt	Date	Temp(1) °C	Winds $m\ S^{-1}$	Weather	Corn A	Corn B	Corn C	Lakes	Forest	Richmond Farms	Mer Bleue
4	AUG 23	20	SSW 7	7/10 Cu			–46				
5/6	AUG 26	18-21	SW 5-8	9/10 Overcast				–1	–2		
7	AUG 31	17	NW 5	4/10 Cloud	–6	–15			–28		–11
8	SEP 8	17	VAR 2	Sunny	–25			2		–19	
9	SEP 10	23	SW 3-5	Sunny	–24	–10			–9		

(1) At flight level CO_2 Fluxes in $kg\ ha^{-1}\ h^{-1}$

TABLE 10

AVERAGE HEAT FLUXES

Flt	Date	Temp(1) °C	Winds $m\ S^{-1}$	Weather	Corn A	Corn B	Corn C	Lakes	Forest	Richmond Farms	Mer Bleue
4	AUG 23	20	SSW 7	7/10 Cu			76				
5/6	AUG 26	18-21	SW 5-8	9/10 Overcast				1	2		
7	AUG 31	17	NW 5	4/10 Cloud	59	106			141		95
8	SEP 8	17	VAR 2	Sunny	84			0		73	
9	SEP 10	23	SW 3-5	Sunny	94	70			134		

(1) At flight level *Heat fluxes in watts m^{-2}*

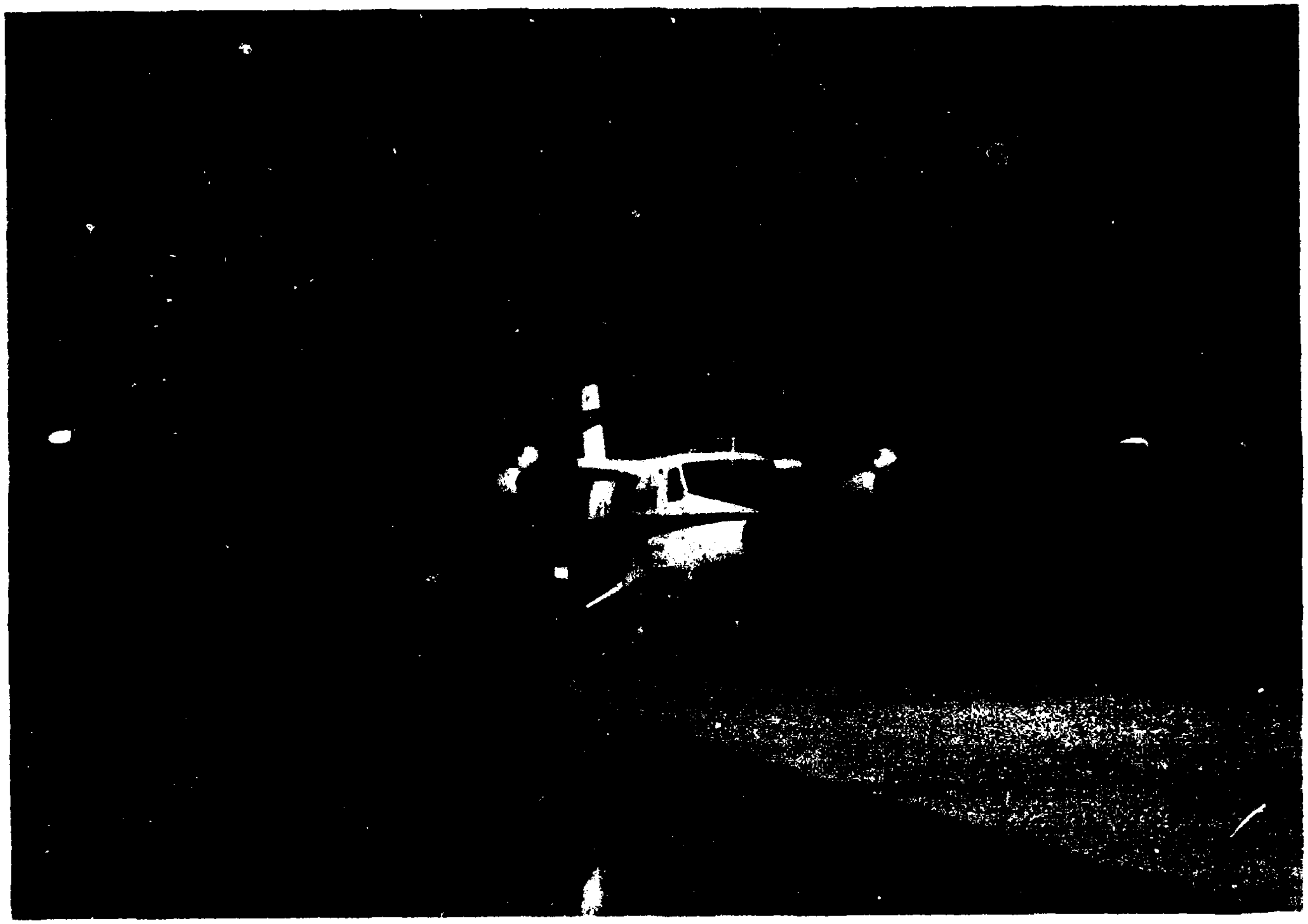


FIG. 1: TWIN OTTER WITH CO_2 ANALYZER MOUNTED ABOVE FUSELAGE

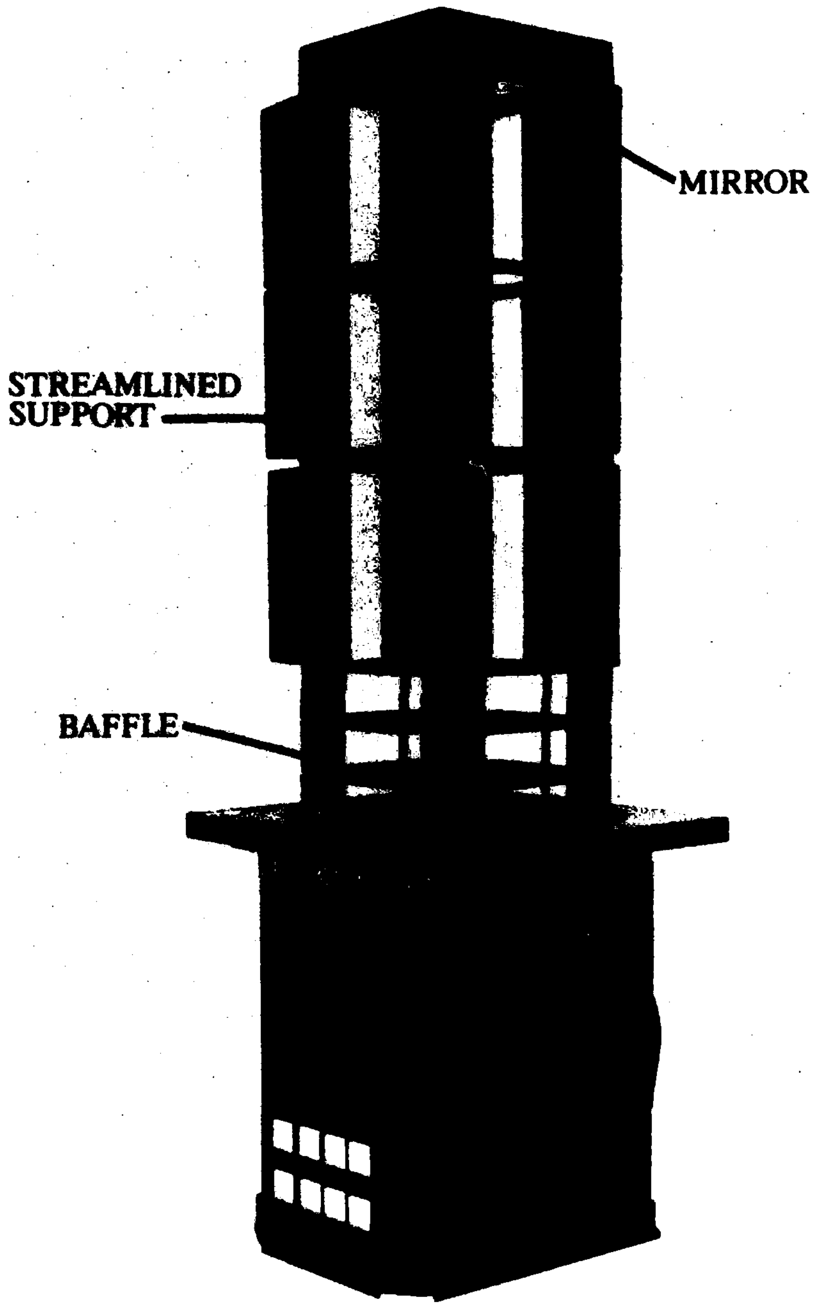


FIG. 2: AGRICULTURE CANADA OPEN-PATH CO_2 ANALYZER

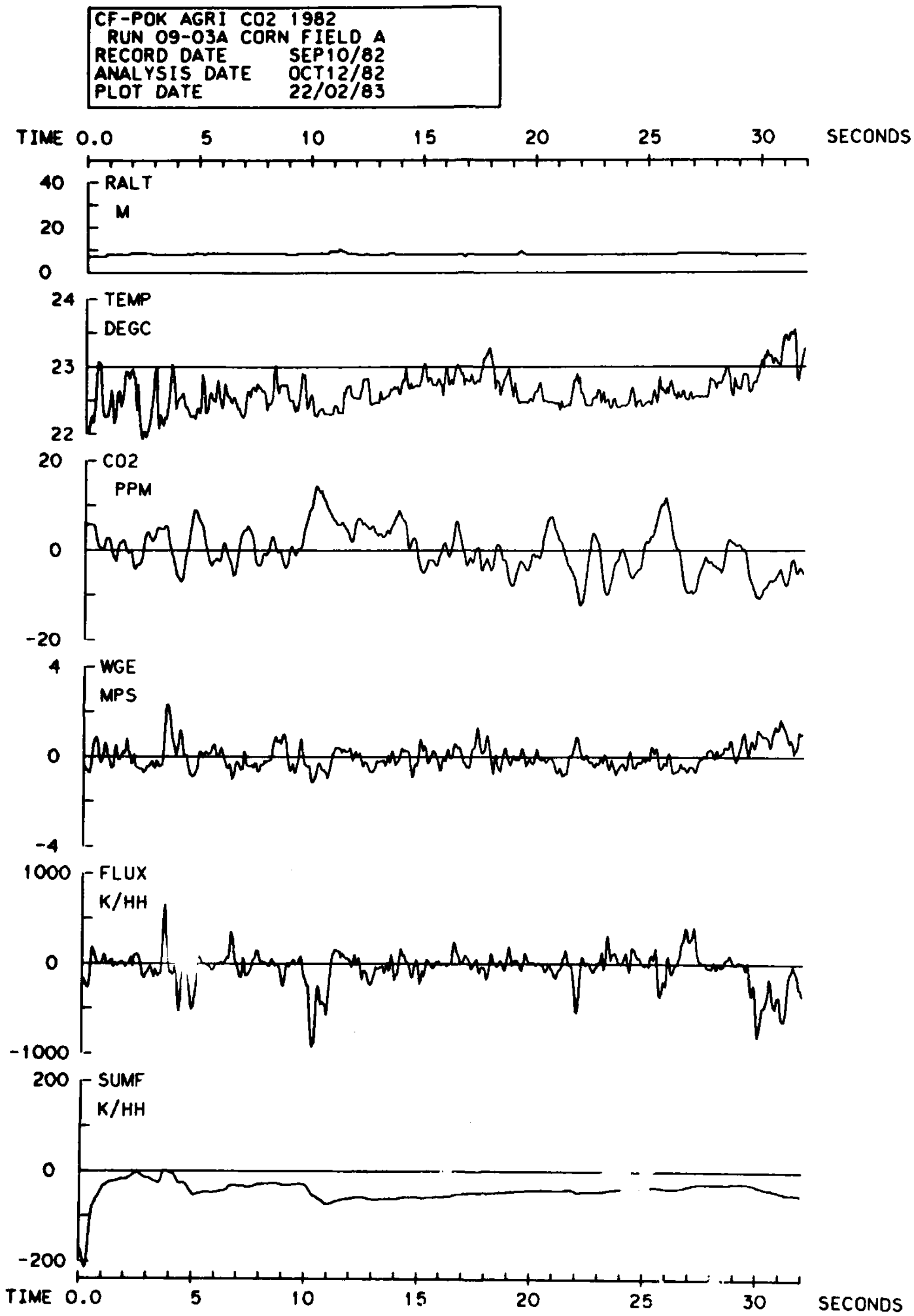


FIG. 3: TIME HISTORIES, CORN FIELD A, RUN 09-03A

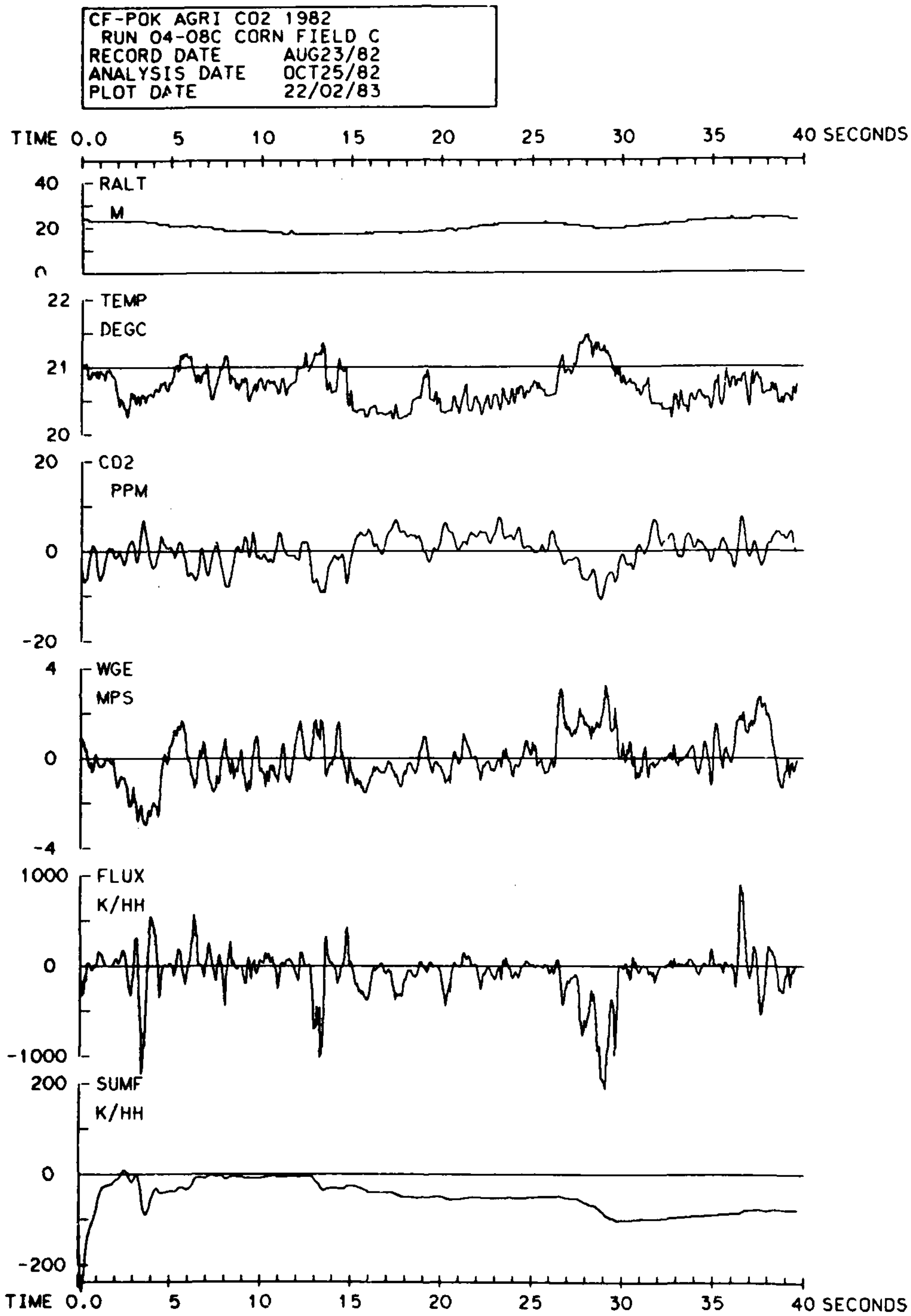


FIG. 4: TIME HISTORIES, CORN FIELD C, RUN 04-08C

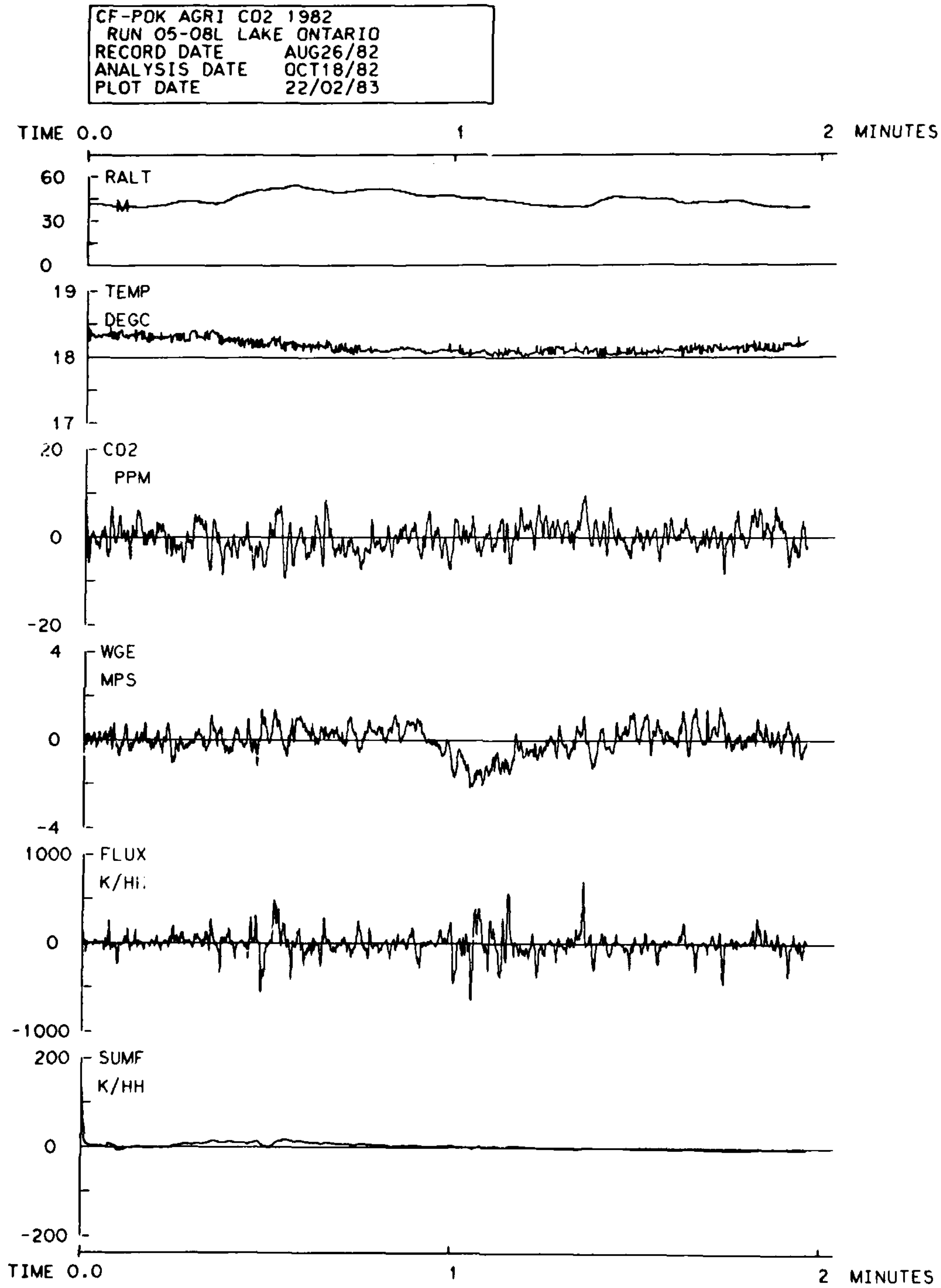


FIG. 5: TIME HISTORIES, LAKE ONTARIO, RUN 05-08L

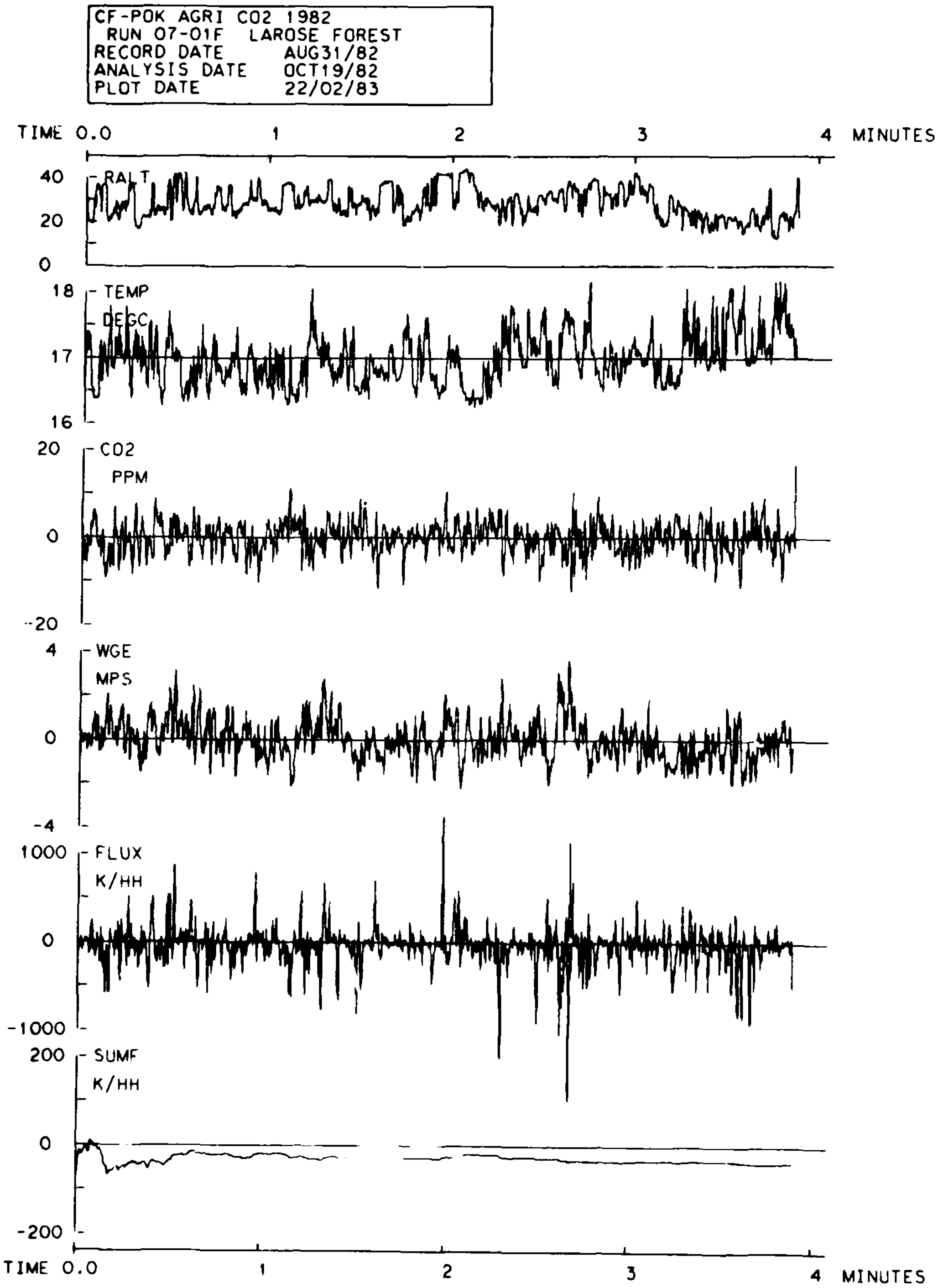


FIG. 6: TIME HISTORIES, LAROSE FOREST, RUN 07-01F

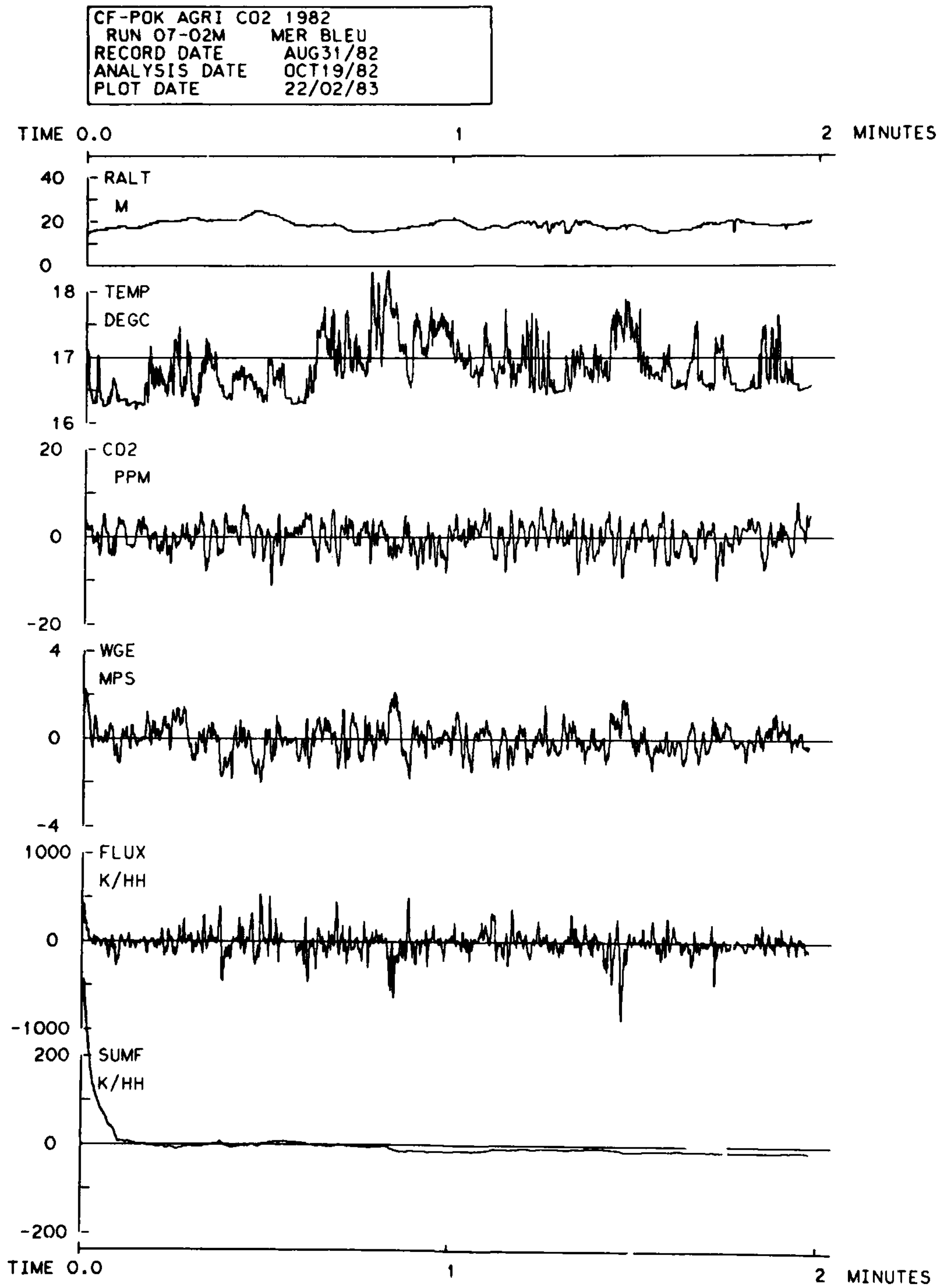


FIG. 7: TIME HISTORIES, MER BLEUE, RUN 07-02M

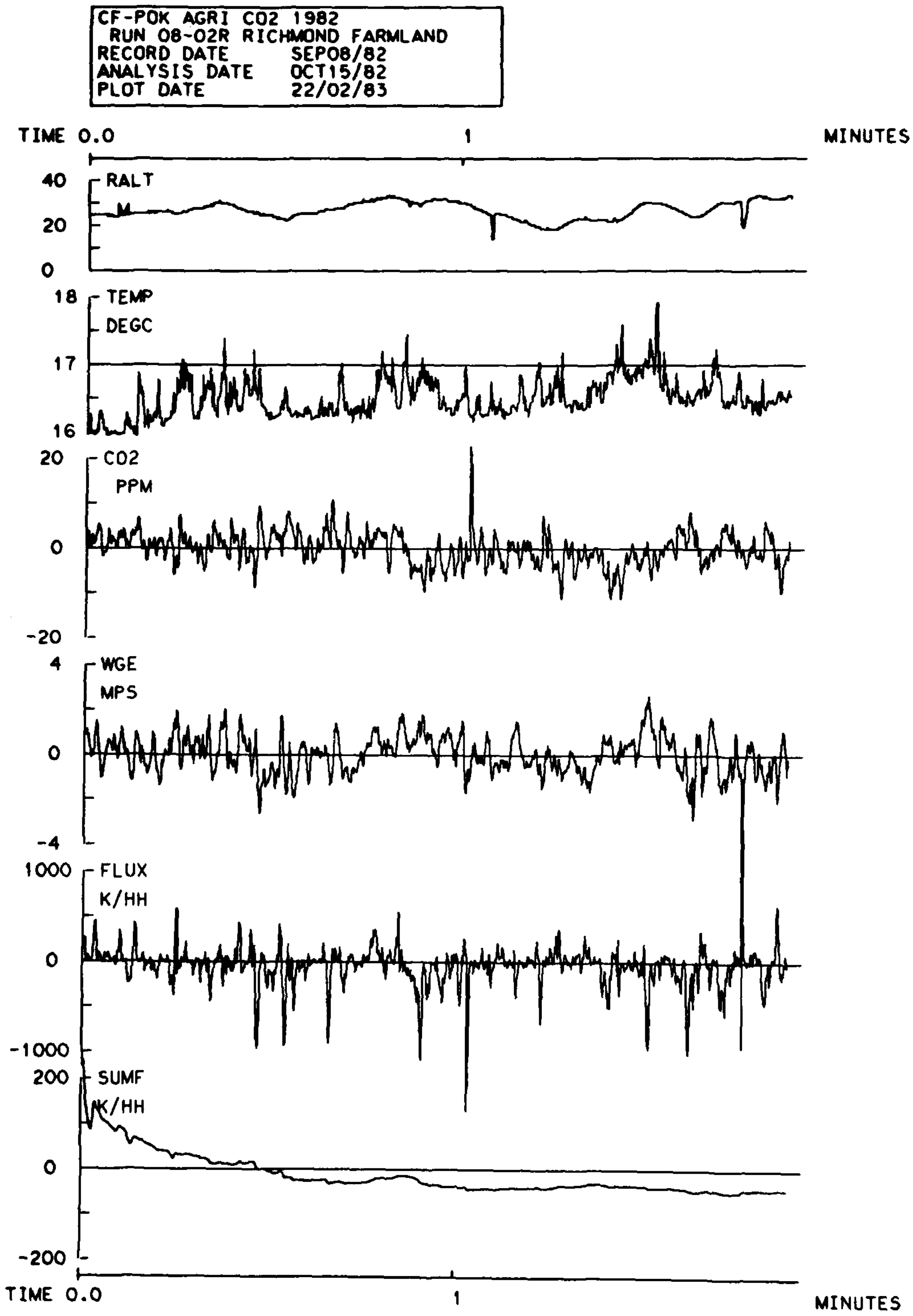


FIG. 8: TIME HISTORIES, RICHMOND FARMLAND, RUN 08-02R

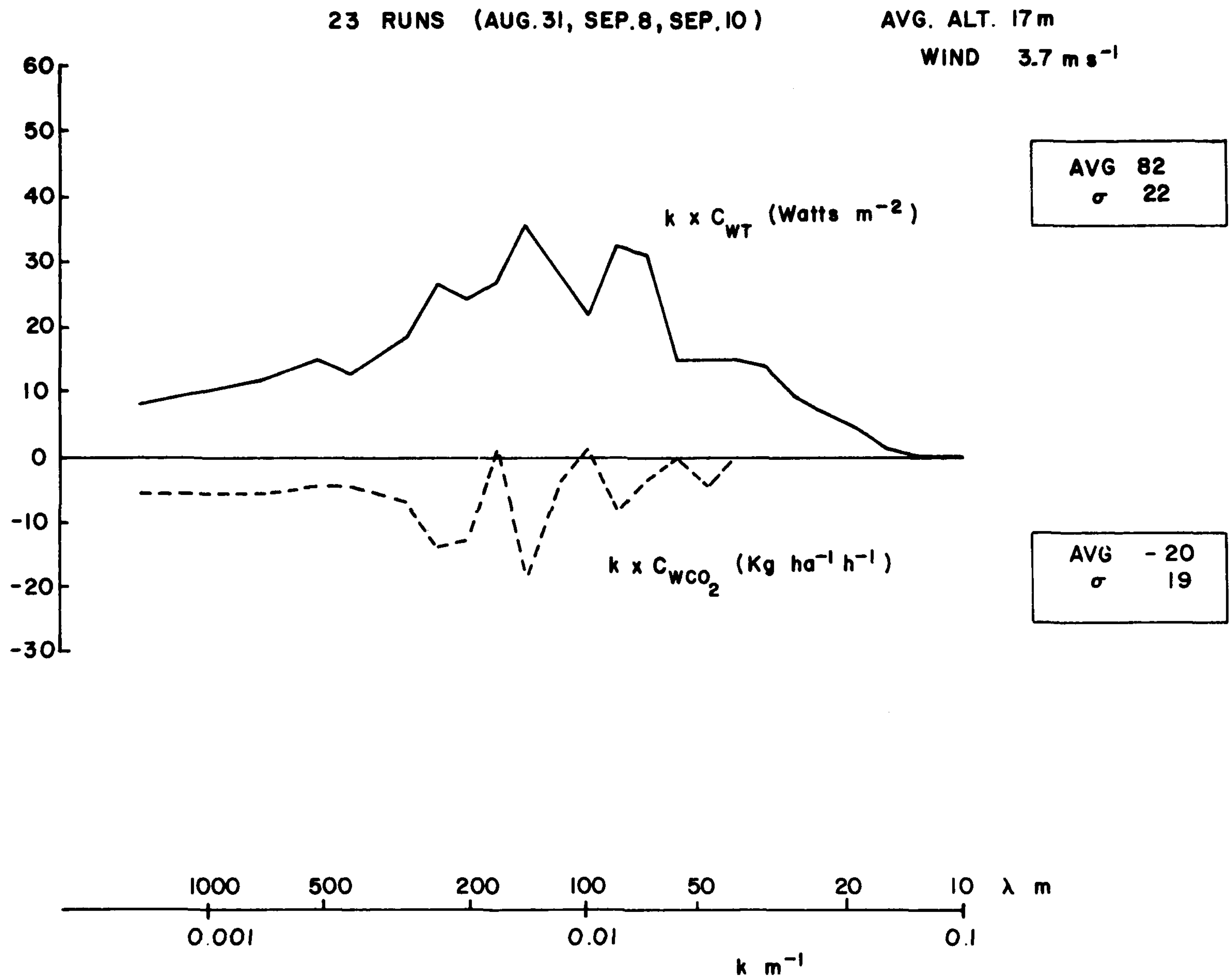


FIG. 9: AVERAGE COSPECTRA - CORN FIELD A

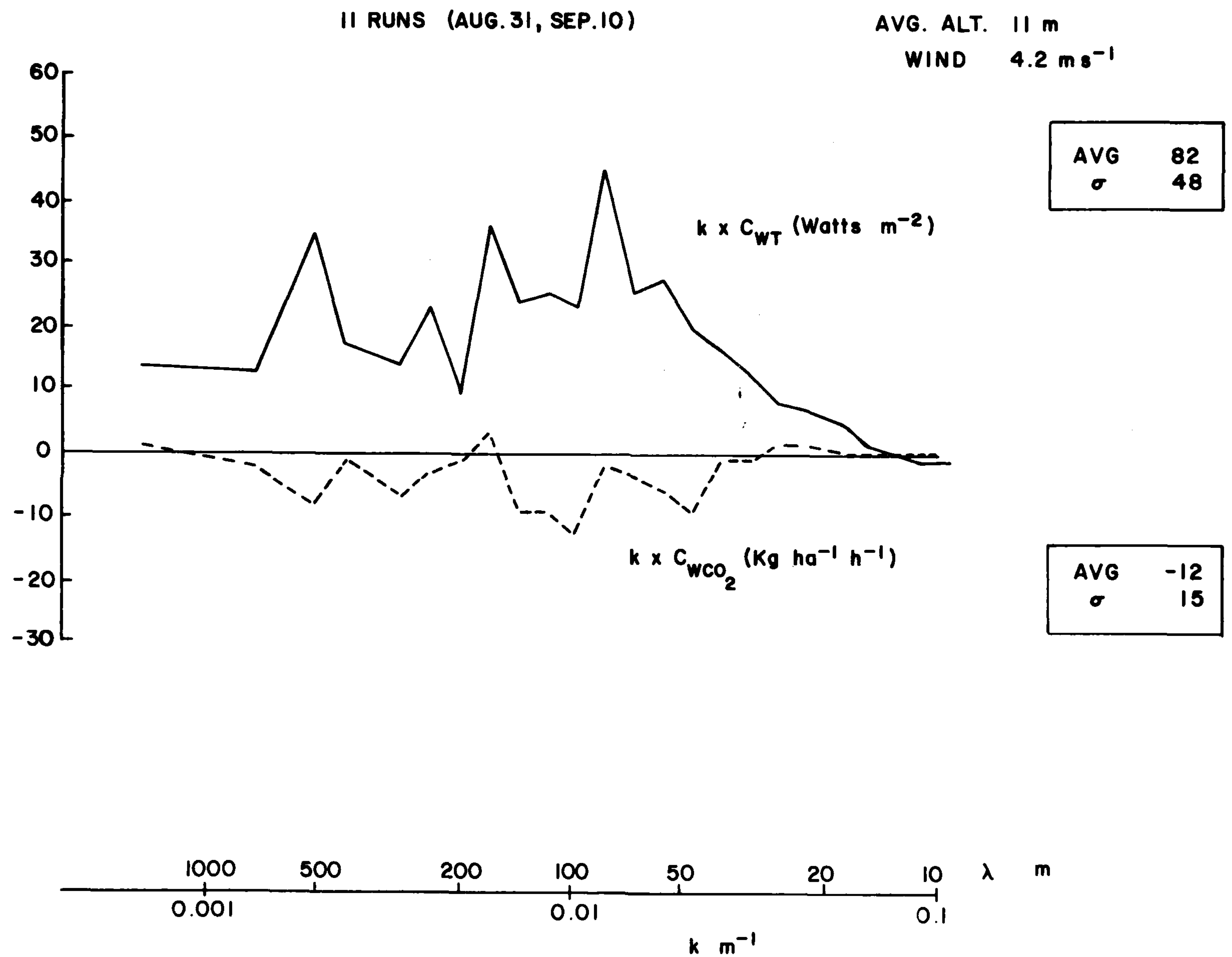


FIG. 10: AVERAGE COSPECTRA - CORN FIELD B

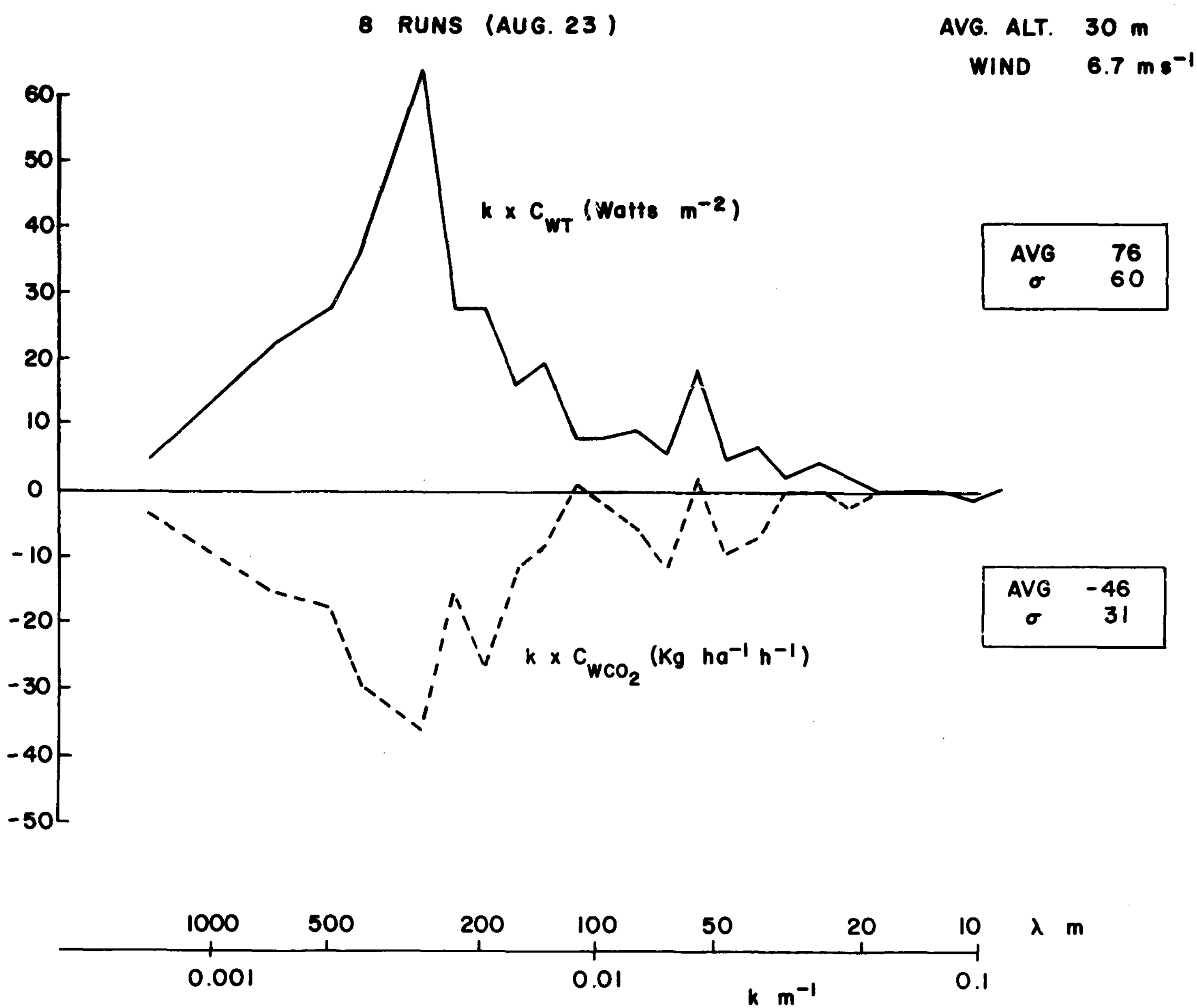


FIG. 11: AVERAGE COSPECTRA - CORN FIELD C

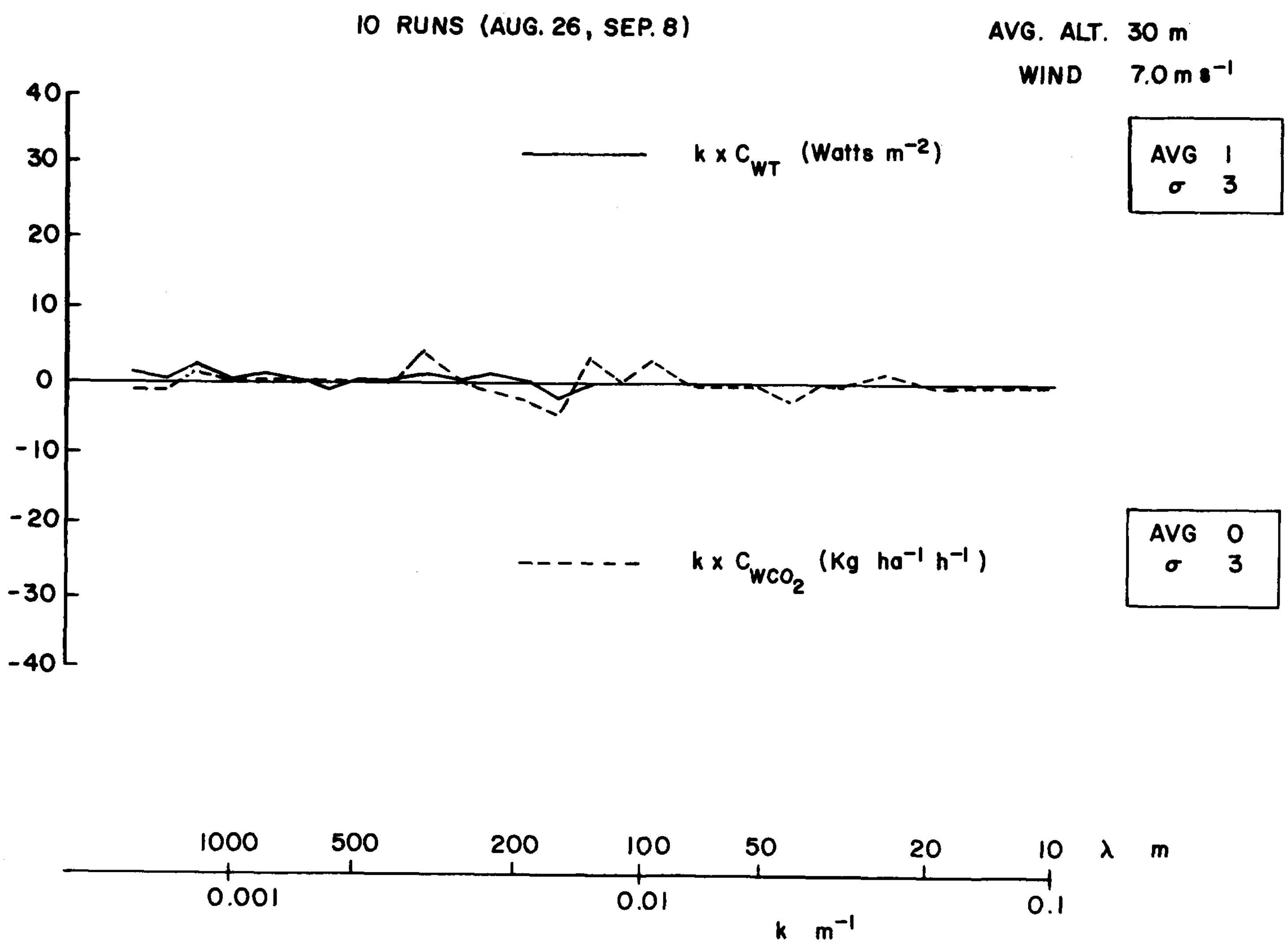


FIG. 12: AVERAGE COSPECTRA - LAKES

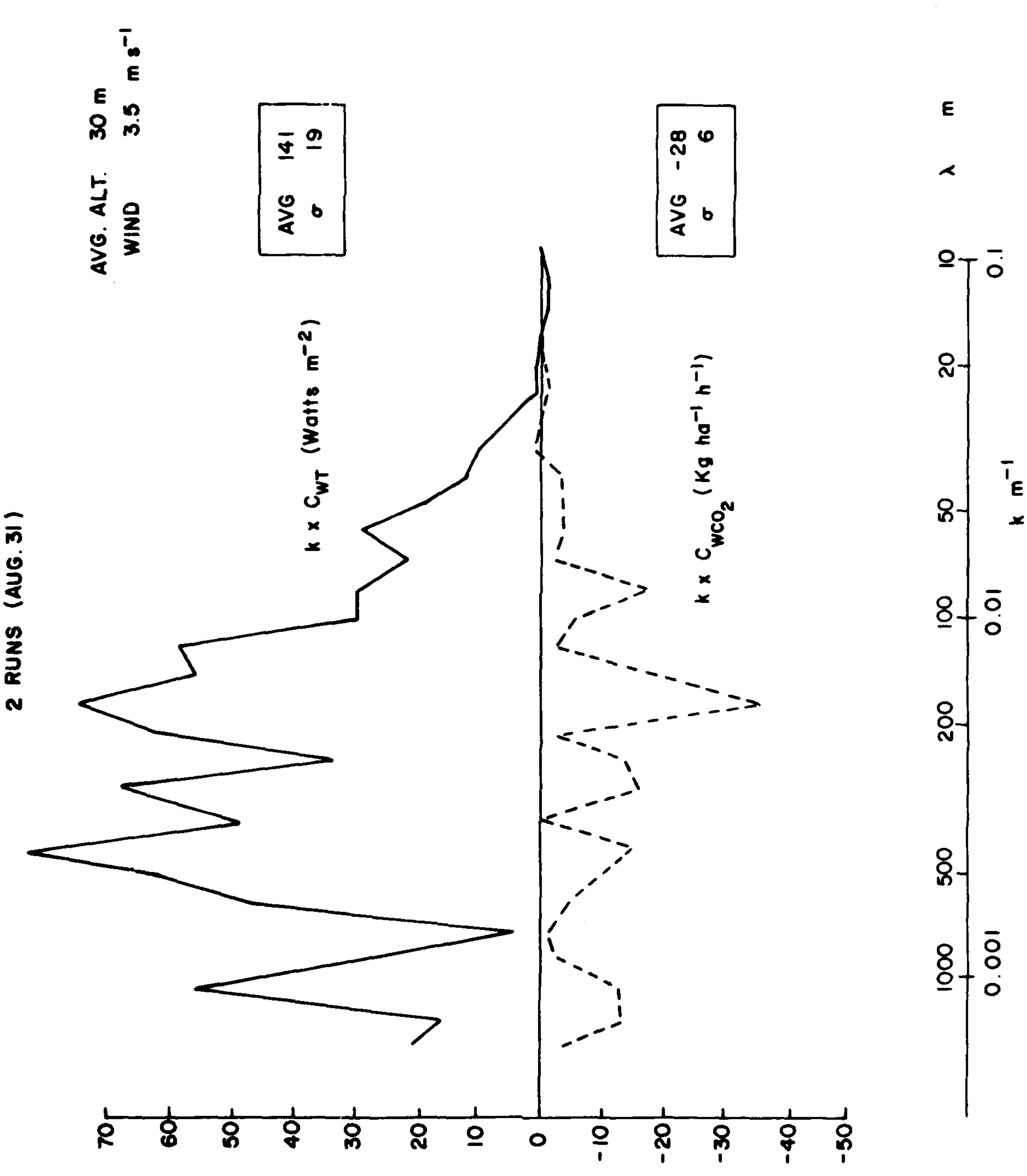


FIG. 13: AVERAGE COSPECTRA - LAROSE FOREST

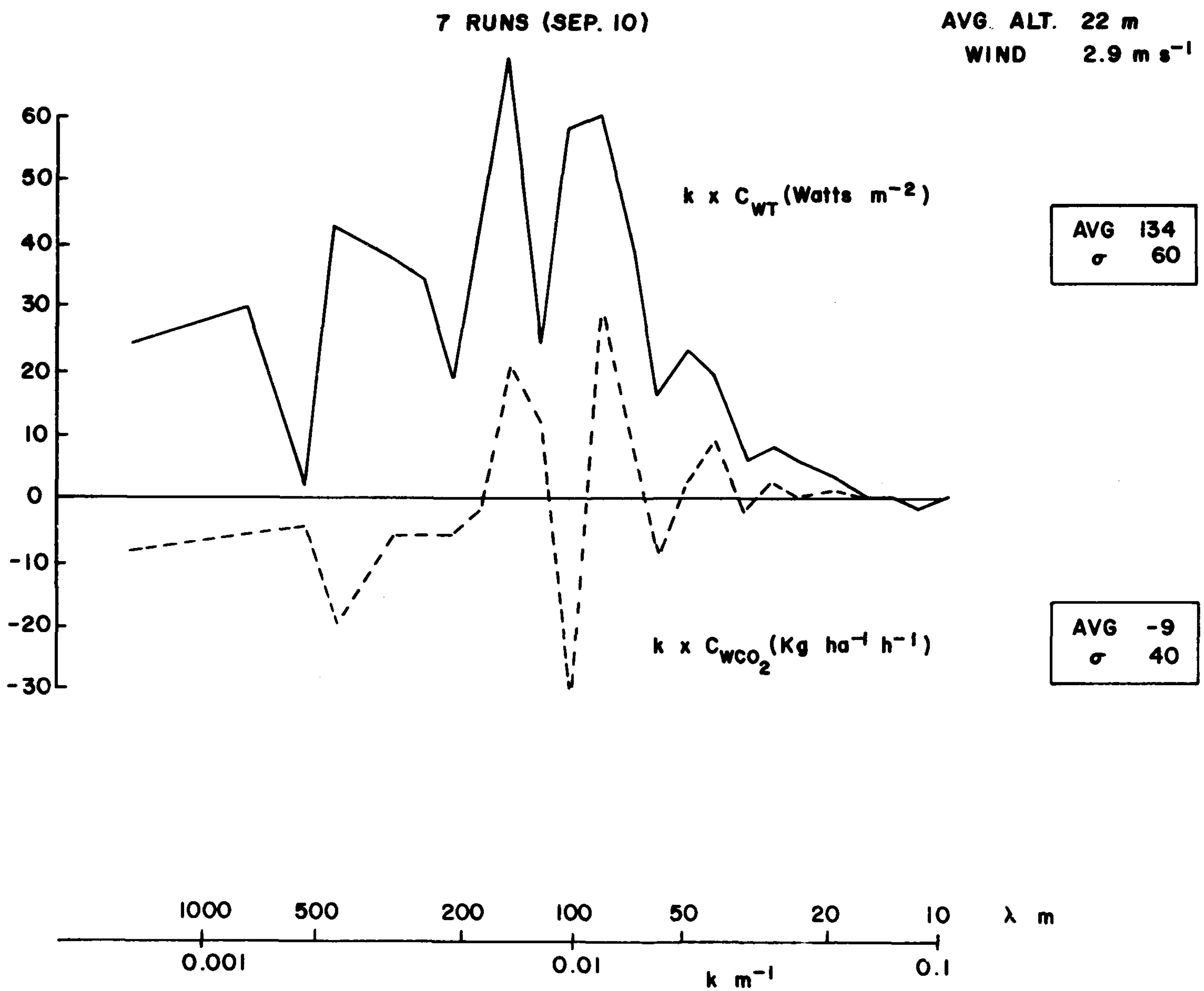


FIG. 14: AVERAGE COSPECTRA - FOREST NEAR B

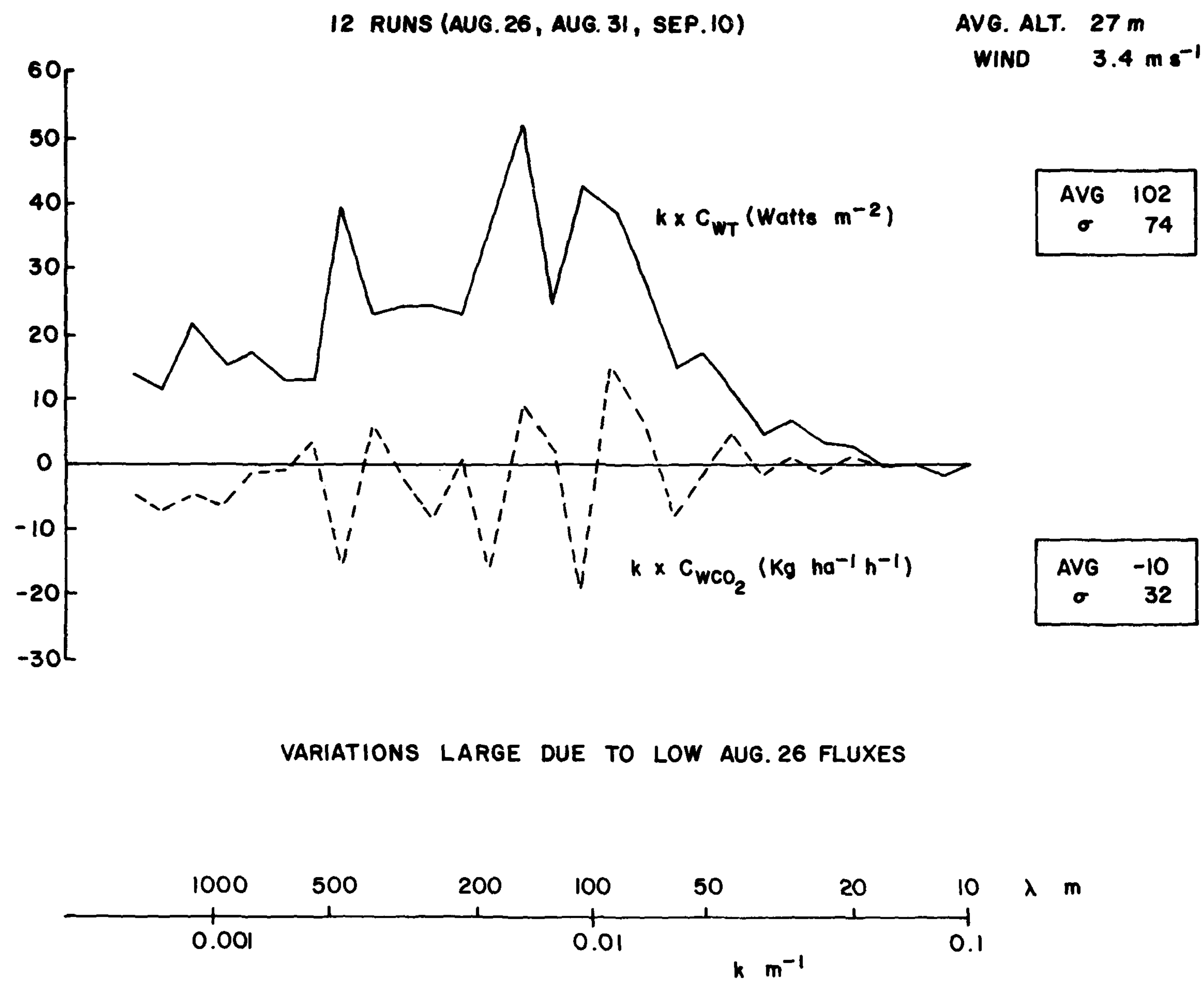


FIG. 15: AVERAGE COSPECTRA - ALL FOREST RUNS

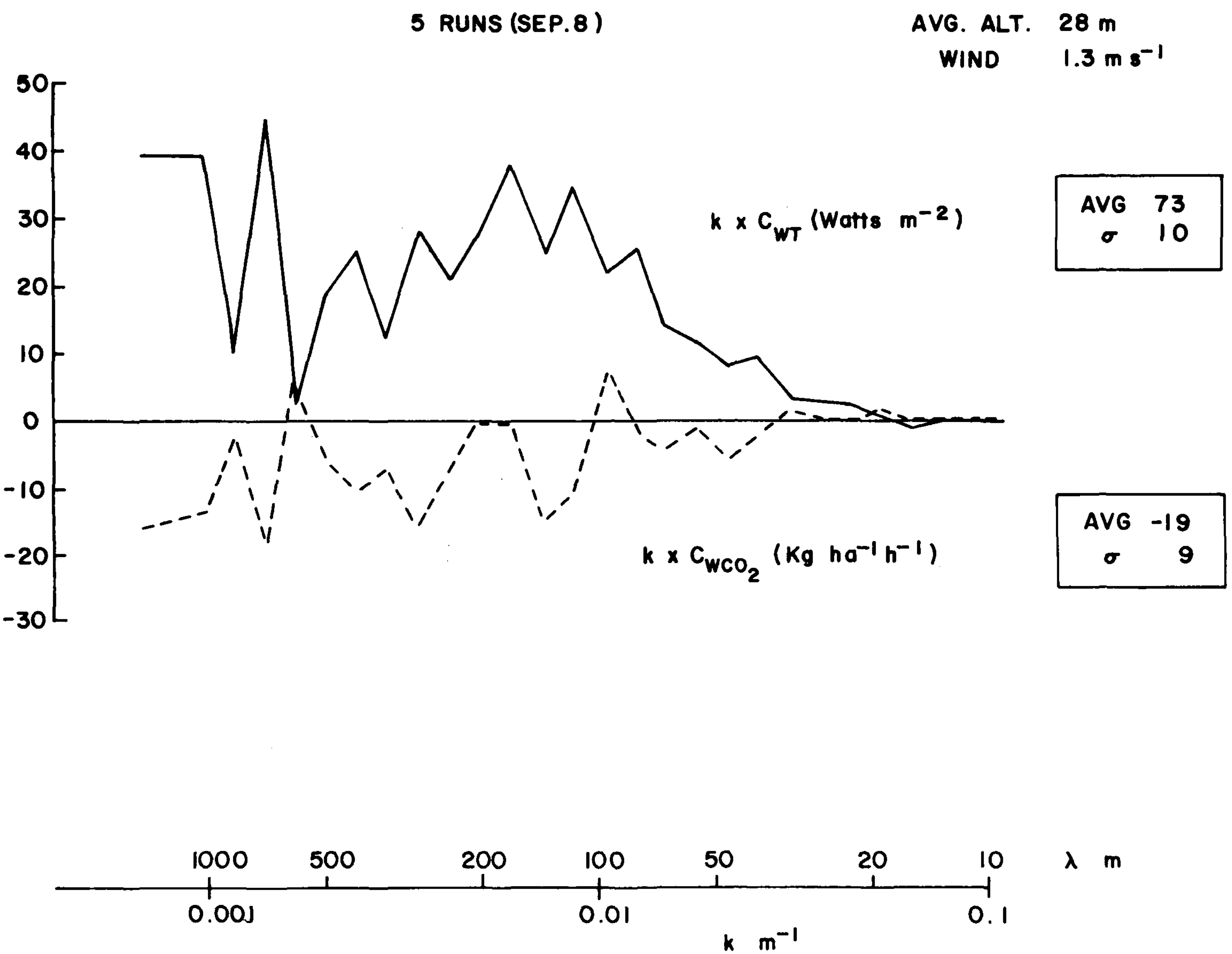


FIG. 16: AVERAGE COSPECTRA - RICHMOND FARMLAND

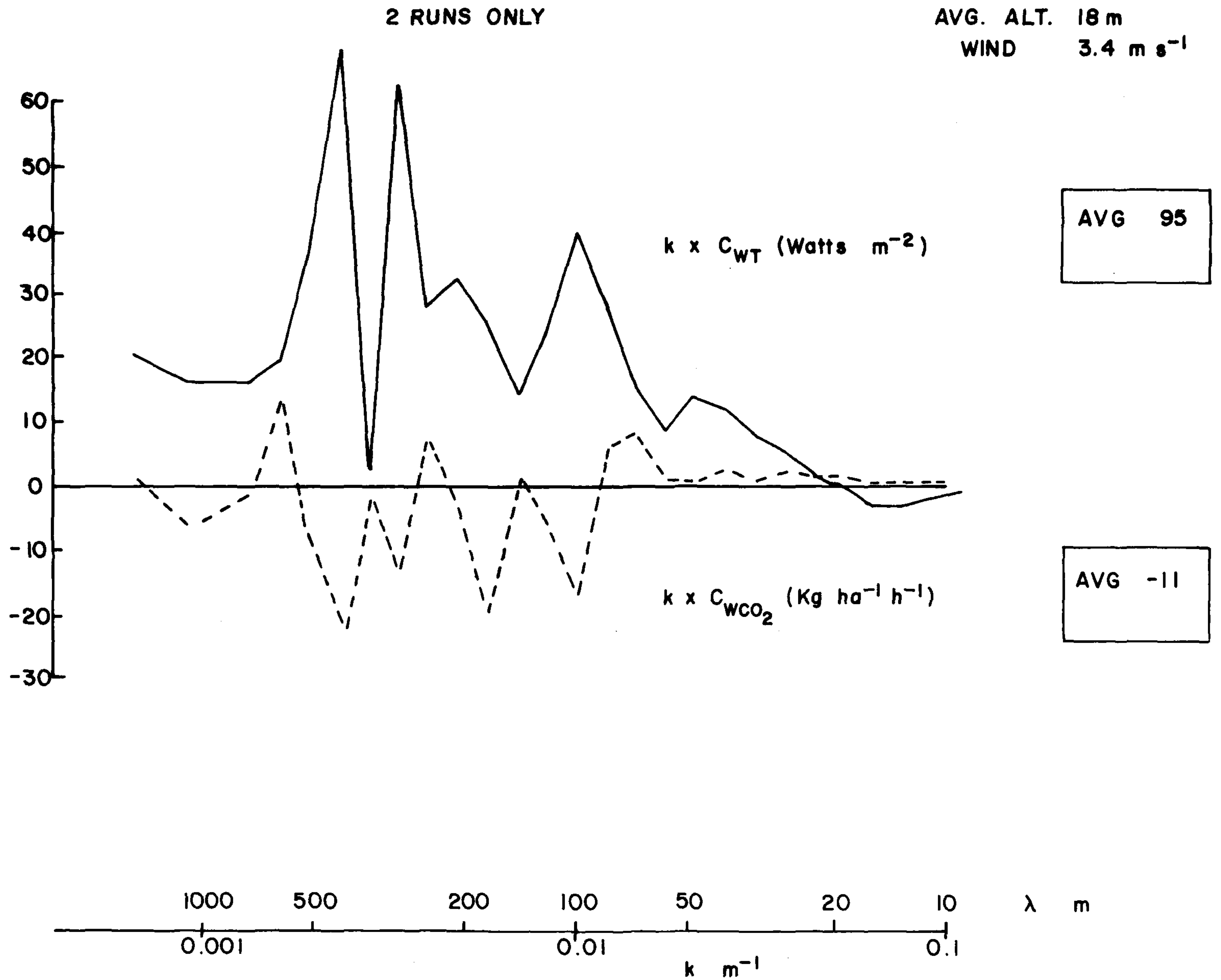
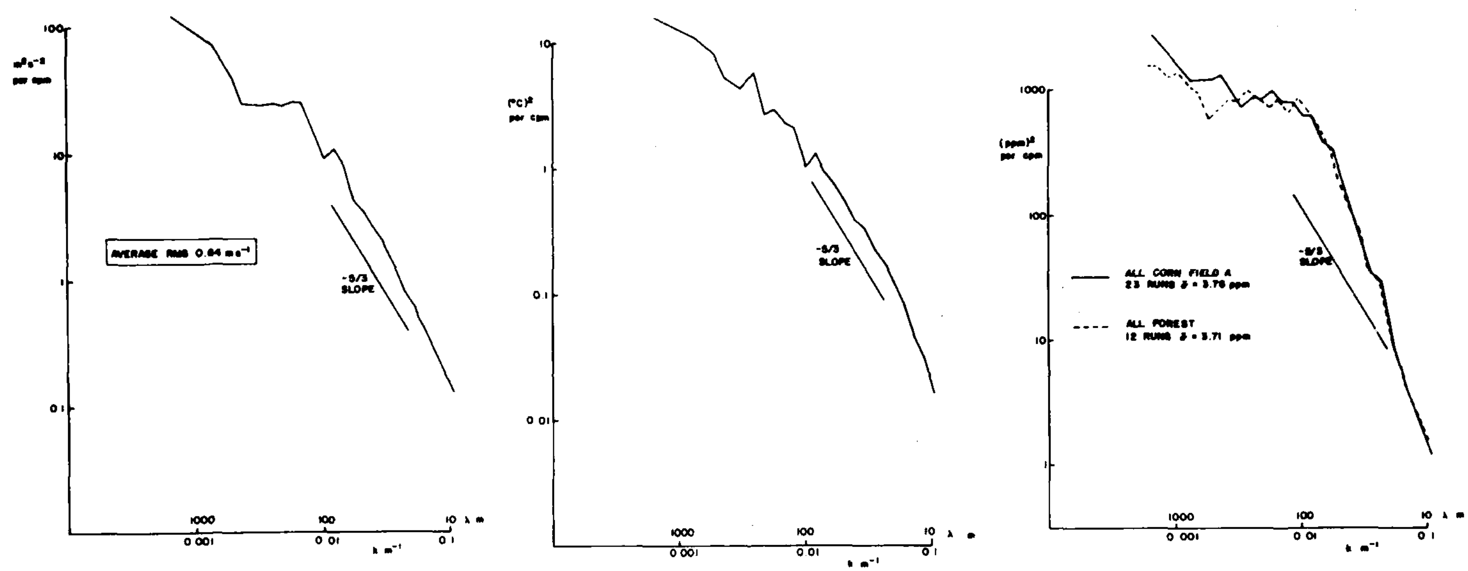


FIG. 17: COSPECTRA - MER BLEUE

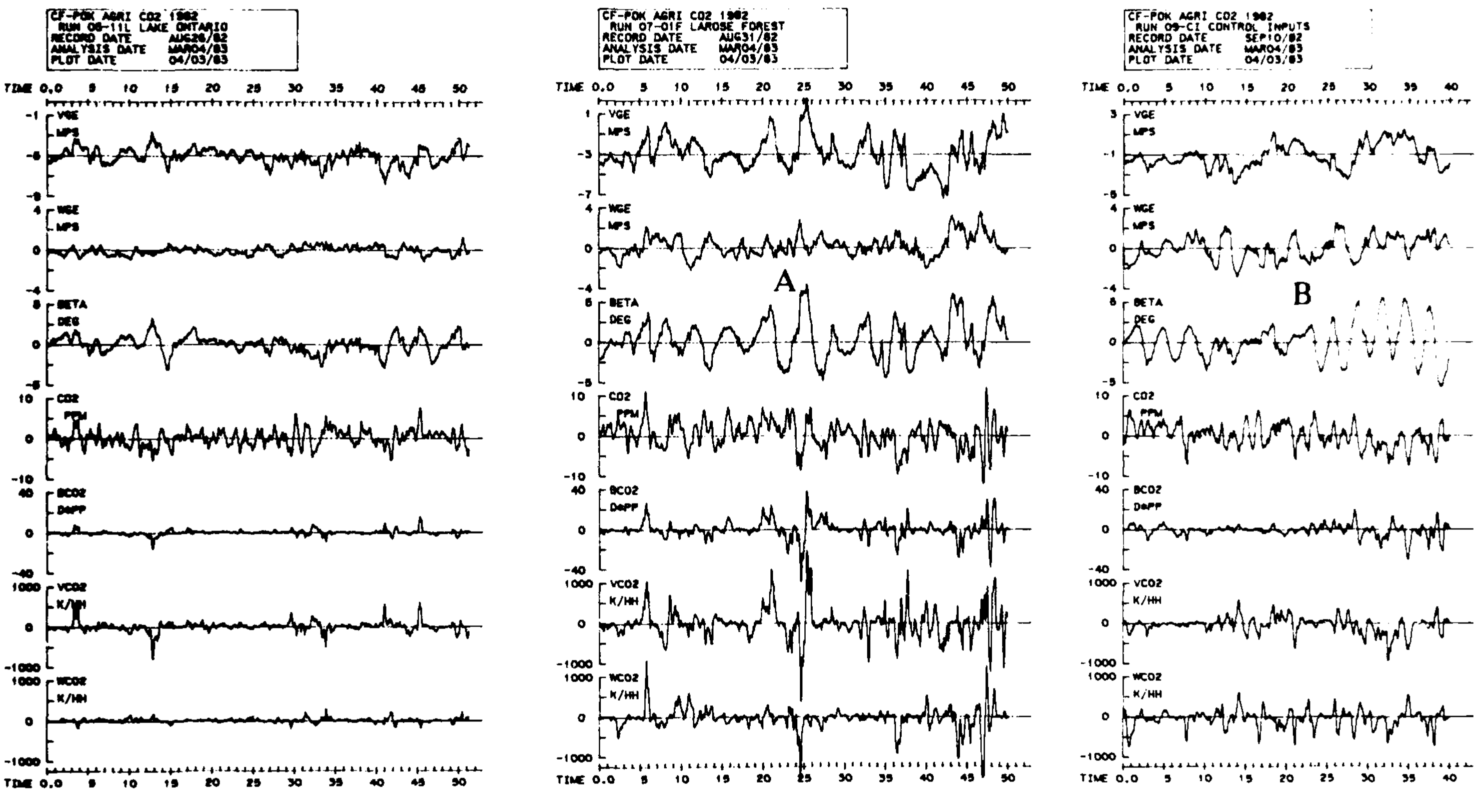


VERTICAL GUST VELOCITY

TEMPERATURE

CARBON DIOXIDE

FIG. 18: AVERAGE POWER SPECTRA



LAKE ONTARIO

$\sigma_\beta = 0.91^\circ$ $\sigma_{co_2} = 2.1$ ppm

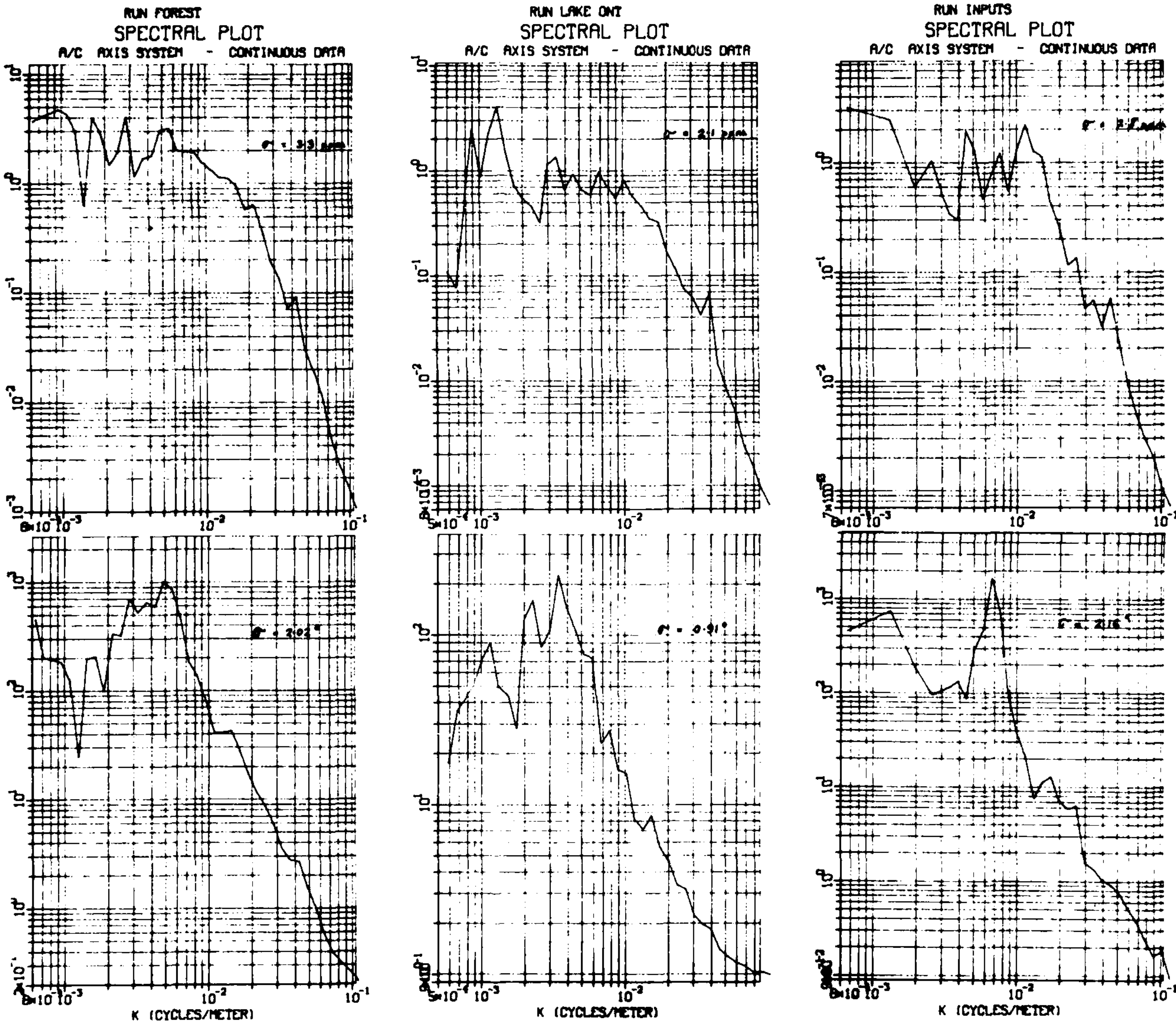
LAROSE FOREST

$\sigma_\beta = 2.02^\circ$ $\sigma_{co_2} = 3.3$ ppm

CONTROL INPUTS

$\sigma_\beta = 2.16^\circ$ $\sigma_{co_2} = 2.8$ ppm

FIG. 19: TIME HISTORIES FOR THREE RUNS USED FOR SIDESLIP STUDIES



CO_2

SIDESLIP ANGLE β

LAROSE FOREST

LAKE ONTARIO

CONTROL INPUTS

FIG. 20: POWER SPECTRA OF CO_2 AND SIDESLIP ANGLE

REPORT DOCUMENTATION PAGE / PAGE DE DOCUMENTATION DE RAPPORT

REPORT/RAPPORT	REPORT/RAPPORT
NAE-AN-16 (1a)	NRC No. 22751 (1b)
REPORT SECURITY CLASSIFICATION / CLASSIFICATION DE SÉCURITÉ DE RAPPORT	DISTRIBUTION (LIMITATIONS)
2 Unclassified	3 Unlimited

TITLE/SUBTITLE/TITRE/SOUS-TITRE

Flight Tests of Instrumentation for Airborne Carbon Dioxide Flux Measurement

4

AUTHOR(S)/AUTEUR(S)

J.I. MacPherson

5

SERIES/SÉRIE

Aeronautical Note

6

CORPORATE AUTHOR/PERFORMING AGENCY/AUTEUR D'ENTREPRISE/AGENCE D'EXÉCUTION

National Research Council Canada
National Aeronautical Establishment — Flight Research Laboratory

7

SPONSORING AGENCY/AGENCE DE SUBVENTION

8

DATE	FILE/DOSSIER	LAB. ORDER COMMANDE DU LAB.	PAGES	FIGS/DIAGRAMMES
83-10			57	20
9	10	11	12a	12b

NOTES

13

DESCRIPTORS (KEY WORDS)/MOTS-CLÉS

1. Carbon dioxide — measurement
2. Carbon dioxide — measurement — flight testing

14

SUMMARY/SOMMAIRE

At the request of Agriculture Canada, the Flight Research Laboratory of the National Aeronautical Establishment (NAE) has operated the Twin Otter atmospheric research aircraft fitted with a CO_2 analyzer in order to assess the feasibility of making airborne carbon dioxide flux measurements. This report will summarize progress to date and present an analysis of the data collected during a series of nine test flights in August and September, 1982.

The experimental results show that it is possible to make realistic measurements of the heat and CO_2 fluxes from an aircraft instrumented to measure vertical gusts. Special tests and analysis procedures were conducted to investigate the accuracy of the carbon dioxide measurements. Recommendations for improvements in the design of future test programs are made.

15

END

FILMED

1-84

DTIC